Recent Accomplishments in Coupling High Resolution Earth System Models Using Advanced Computational Technologies

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Description and Objectives

Apply advanced computational technologies to the problem of coupling high-resolution Earth system models

Combine the emerging technologies of the Earth System Modeling Framework (ESMF), the Land Information System (LIS) and the Grid Analysis and Display System (GrADS)/Distributed Oceanographic Data System (DODS) and couple them to the Weather Research and Forecasting (WRF) model and the Goddard Cumulus Ensemble (GCE) model to enable high-resolution modeling

Questions Examined

- Do the initial lower boundary conditions from Land Surface Model (LSM) spin-ups enhance the modeling of convection?

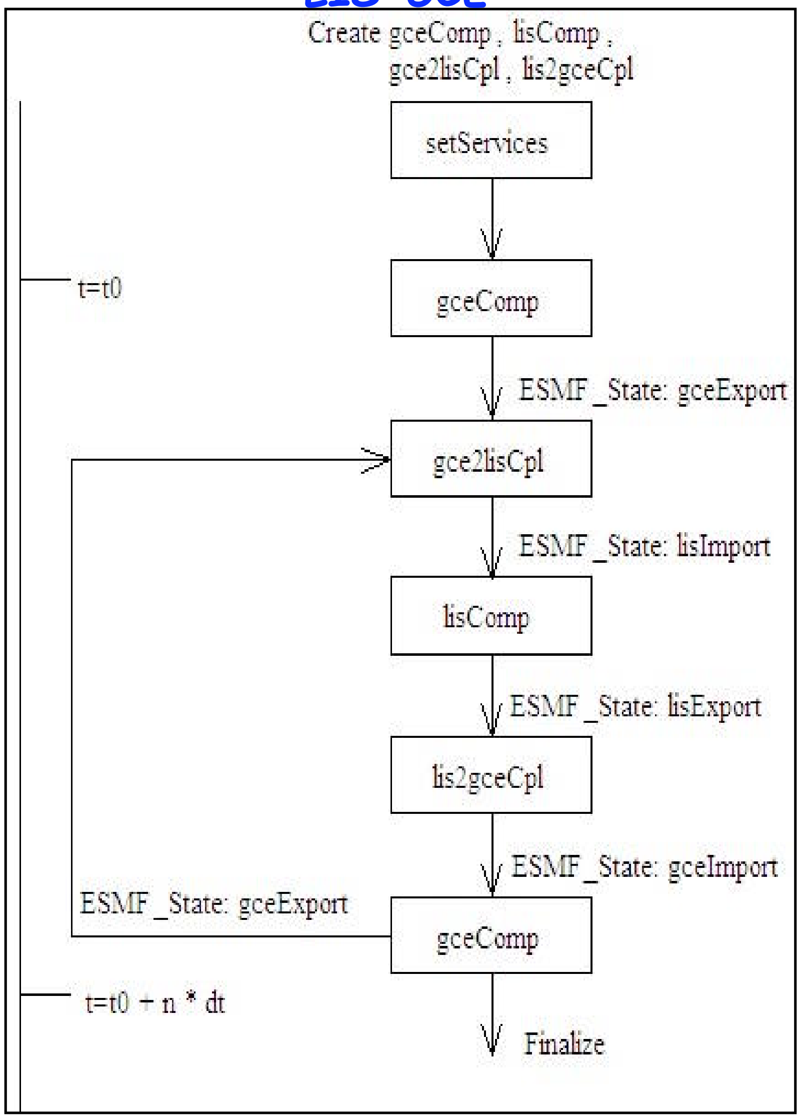
- Does higher resolution forcing employed in the spin-up integrations improve the integration results ?

- Do different LSMs have an impact on the model's ability to simulate convection?

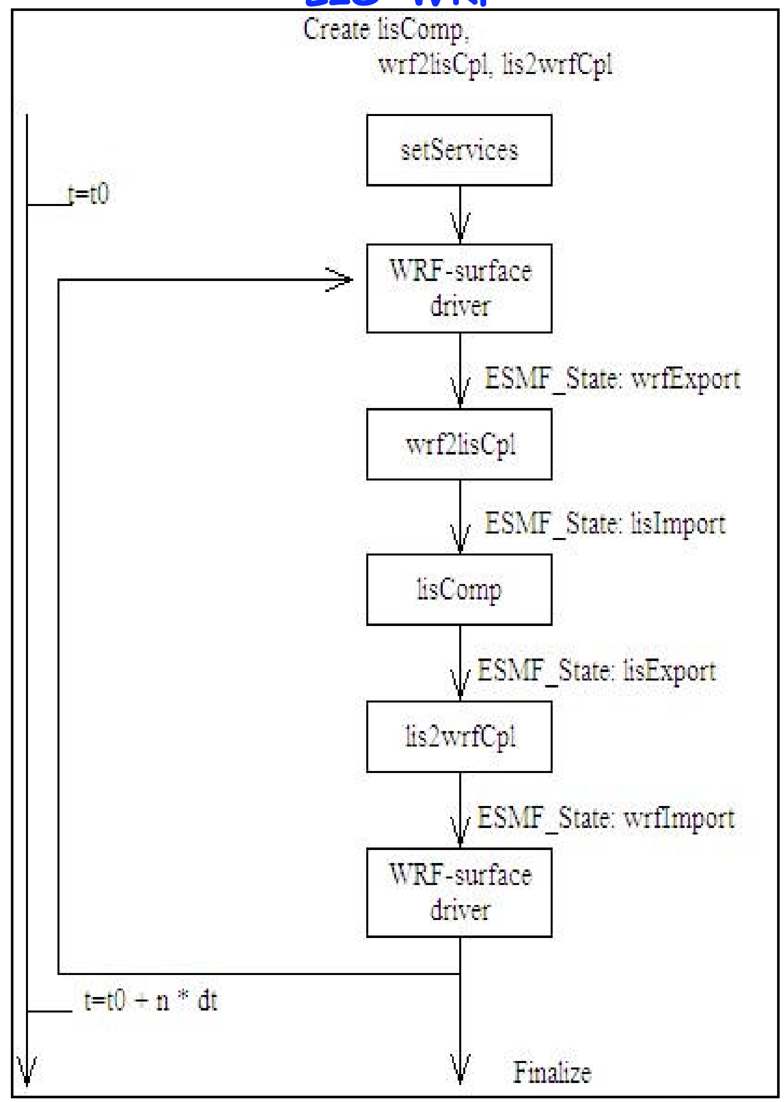
- Does the addition of higher resolution parameter data enhance the predictability?

Design of the Component Interactions Sequence for the Coupled System

LIS-GCE



LIS-WRF



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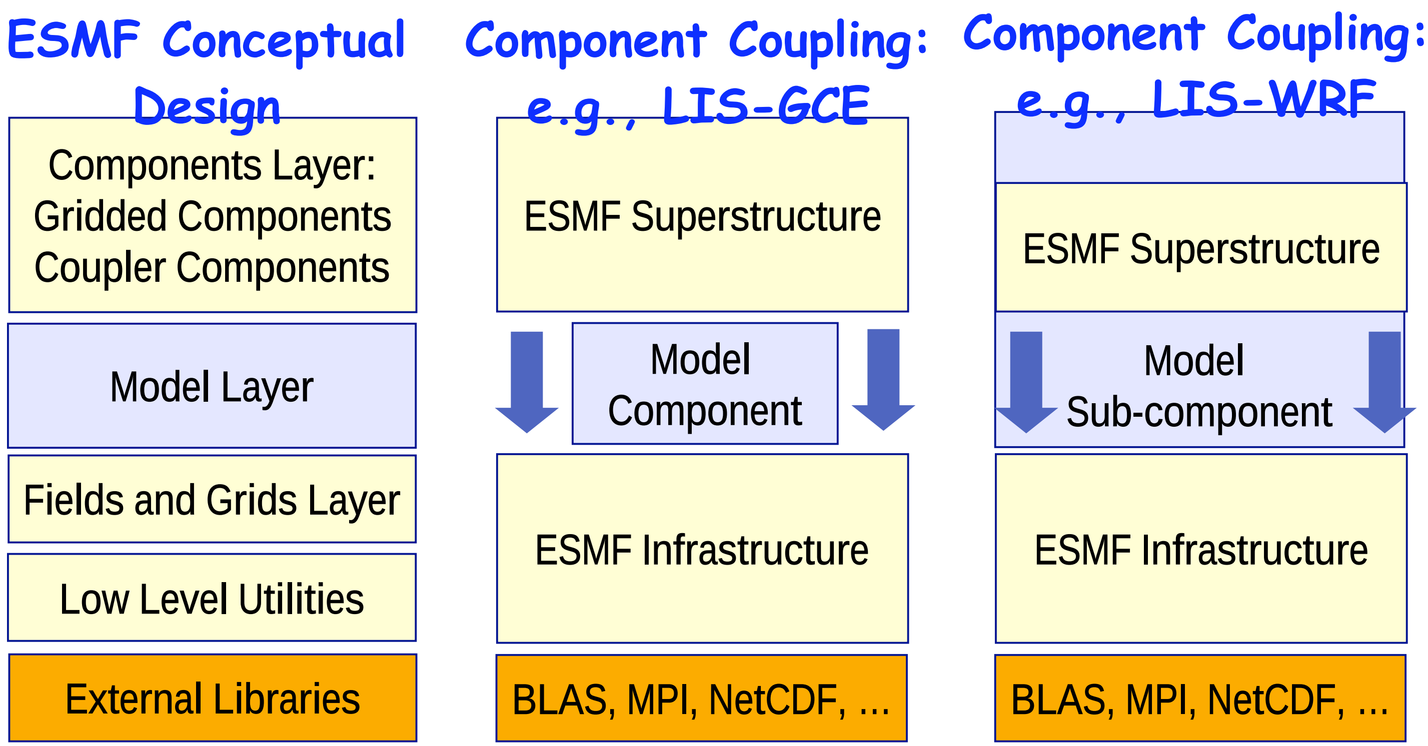
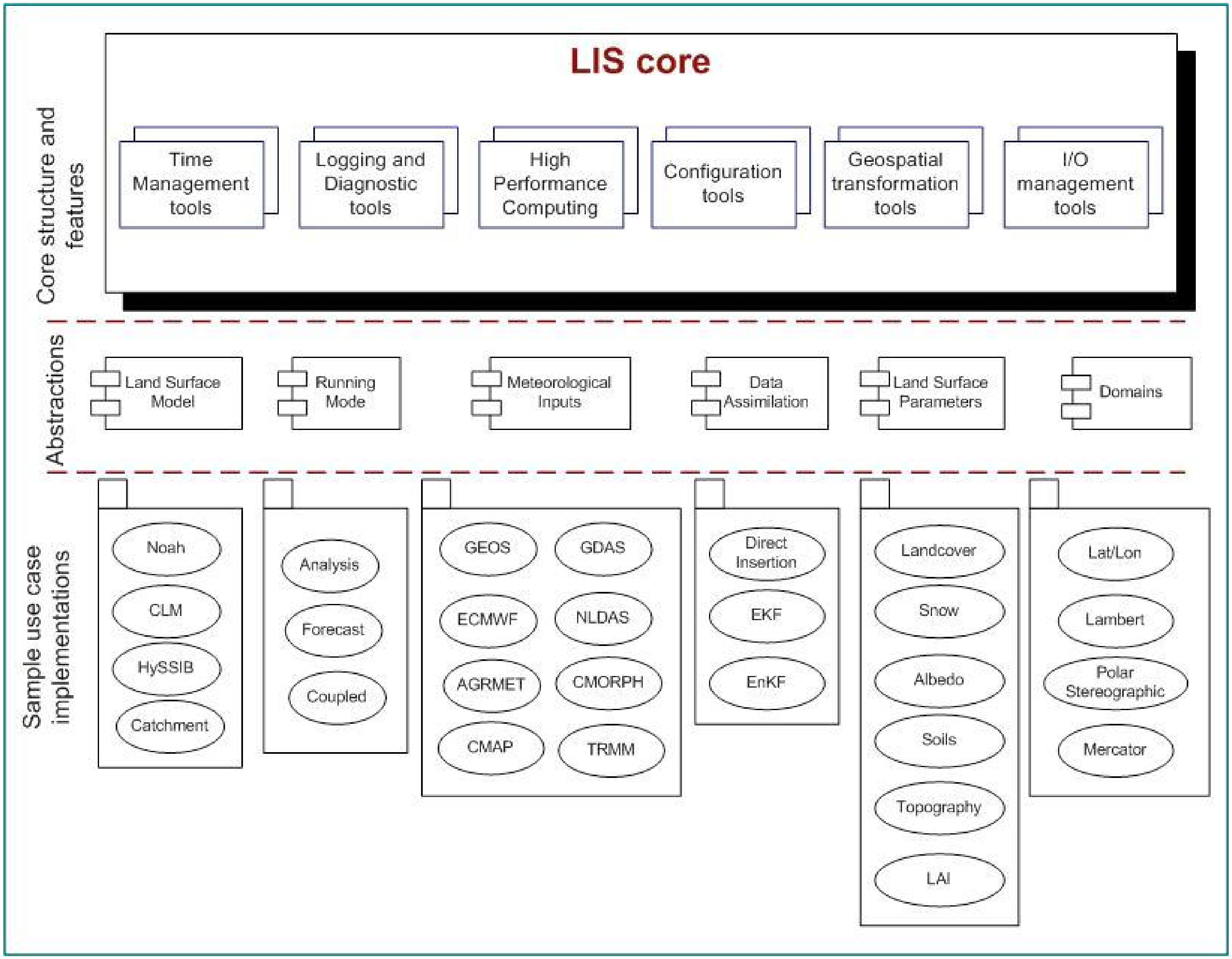
ESMF Coupling Schematic

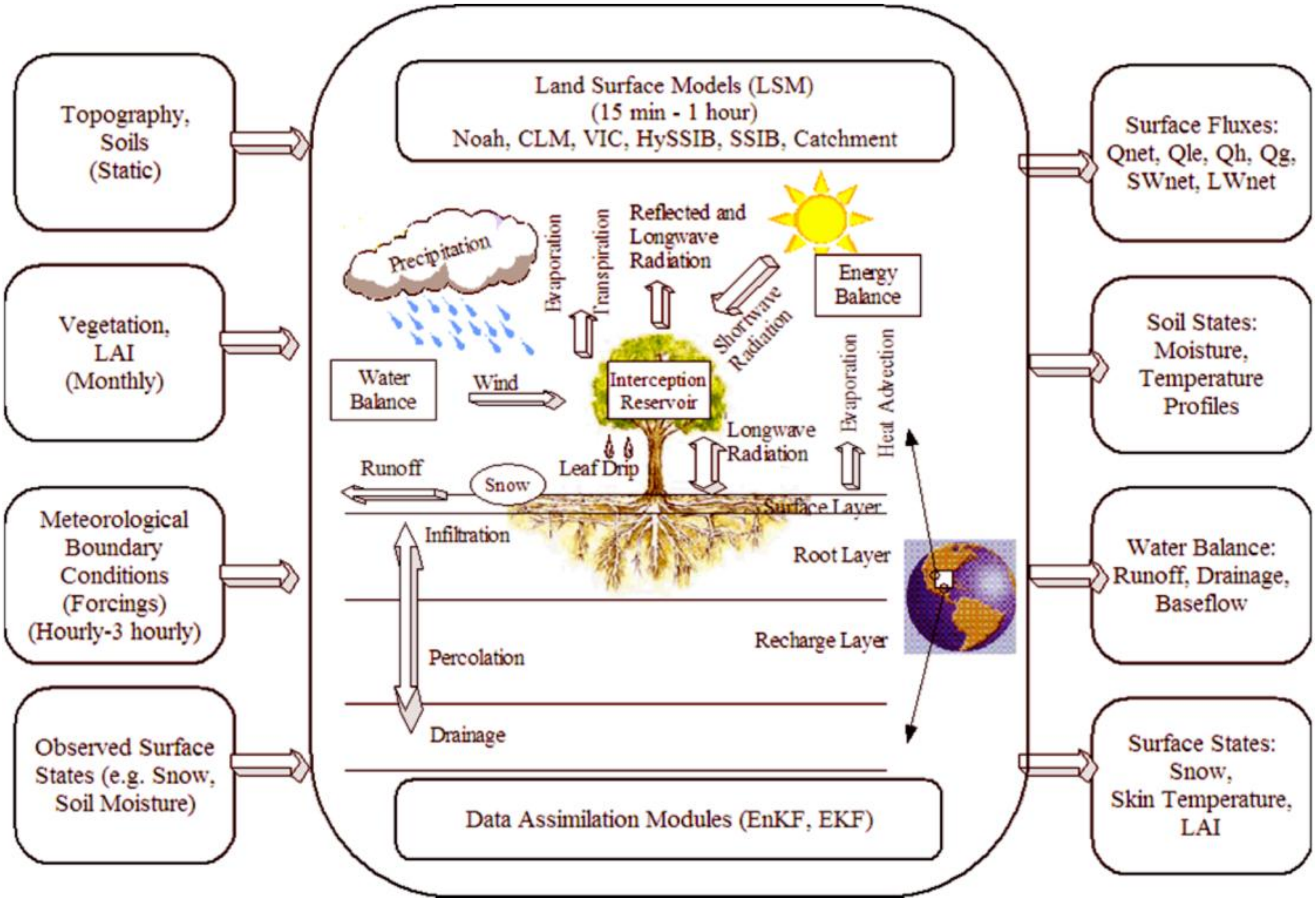


Structure of the LIS Framework



Kumar et al., 2006, in preparation.

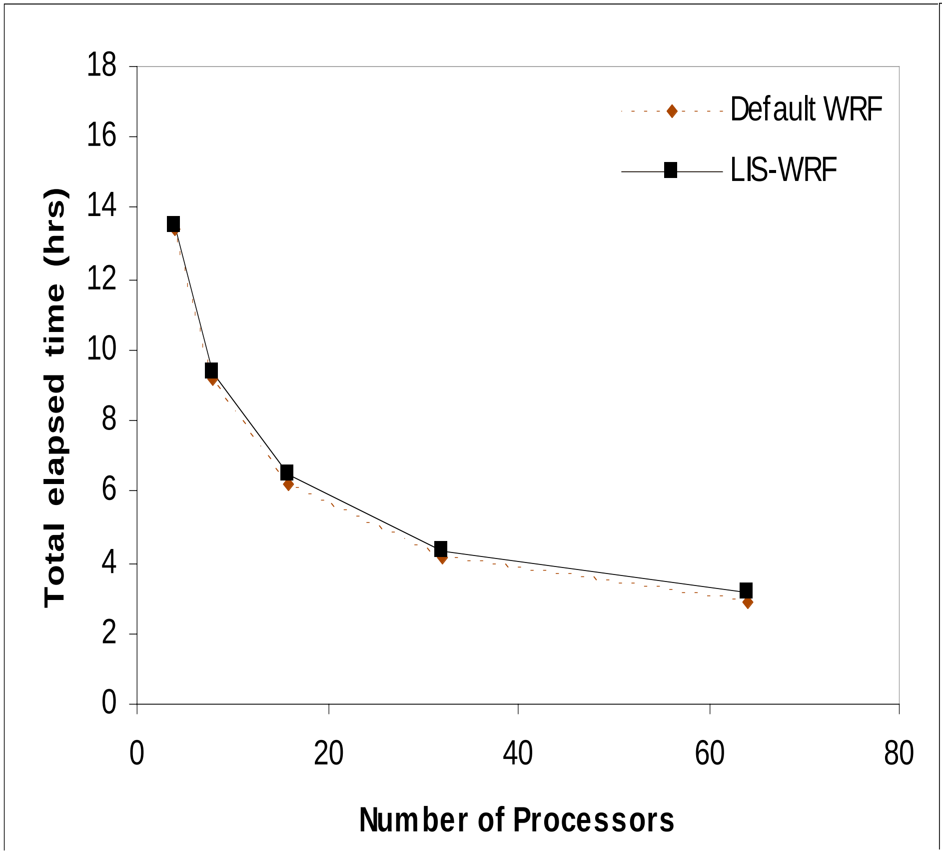
Overview of LIS

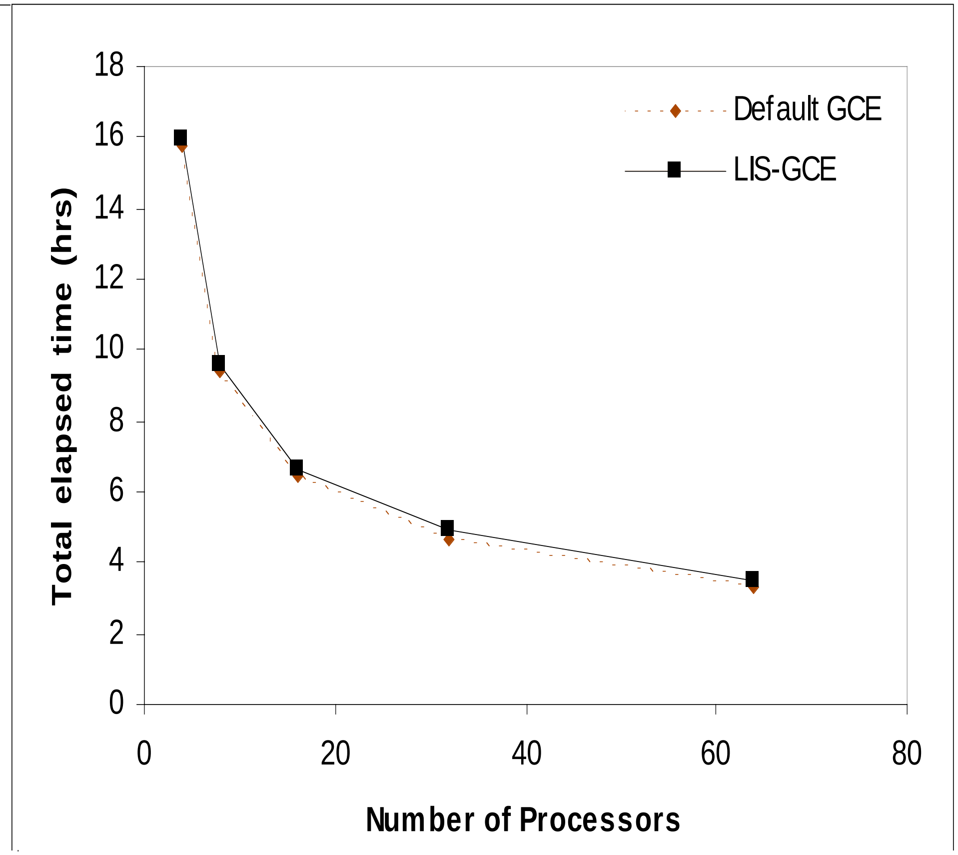


Features Added for LIS-WRF Coupling

- Support for multiple projection types including lambert conformal, polar stereographic, mercator, and lat/lon grids
- Incorporation of the CLM2 land surface model
- Support for nested grids
- Increased resolution parameter data sets such as AVHRR and MODIS collection 3 LAI and Greenness Fraction
- Added Goddard Cumulus Ensemble Model Microphysics

Performance Measures
Impact of ESMF on Coupled Performance

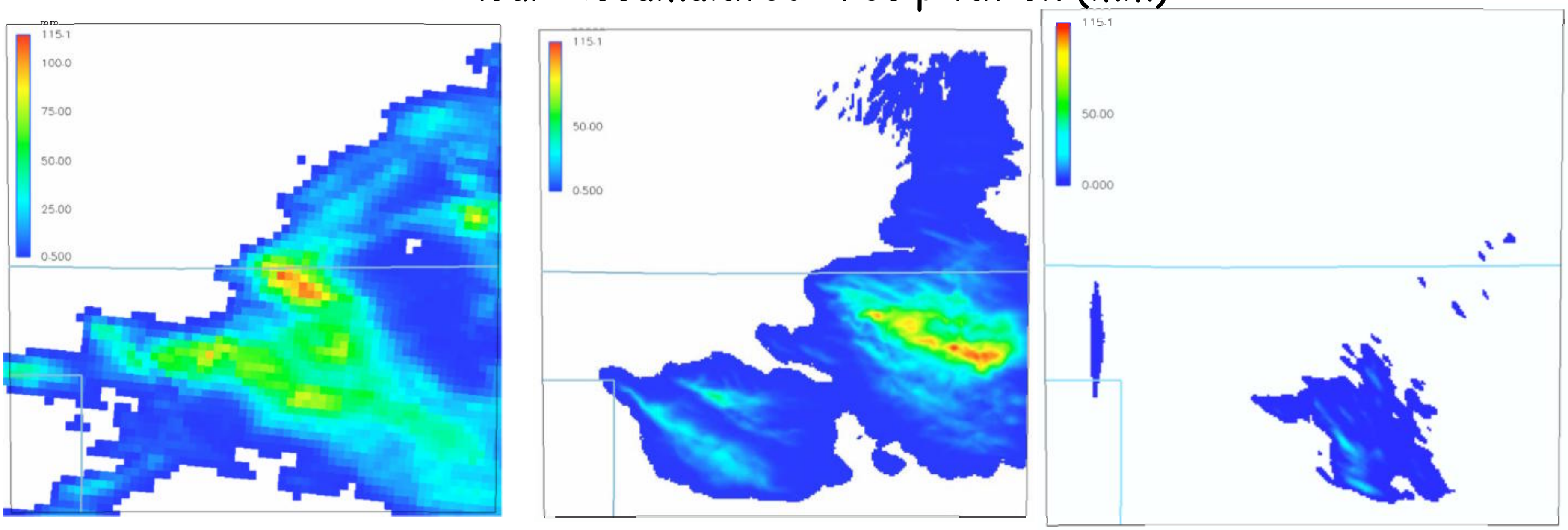




What are Spin-ups?

- Long term integrations (from 2-17 years) using LIS offline forced by observations and employing various parameter data
- WRFSI is the Weather Research and Forecast Model (WRF) Standard Initialization

24 hour Accumulated Precipitation (mm)



STIV Observations (4km gridded) LISWRF with LIS initial conditions WRFSI soils climatology

Experimental Design & Notation

Simulation Symbol	Forcing	Forcing Resolution	Soils	Soil Resolution
WRFSI	N/A	N/A	N/A	N/A
F0	GDAS	2.5 degree, 3 hour	FAO	5 minute
F1	GDAS	2.5 degree, 3 hour	STATSGO	1km
F2	GOES + STAGEIV	1/8th degree, 1 hour	FAO	5 minute
F12	GOES + STAGEIV	1/8th degree, 1 hour	STATSGO	1km

WRFSI=WRF Standard Initialization

GOES = Geostationary Operational Environmental Satellite;

STAGEIV = NCEP's Radar + raingauge national radar mosaic

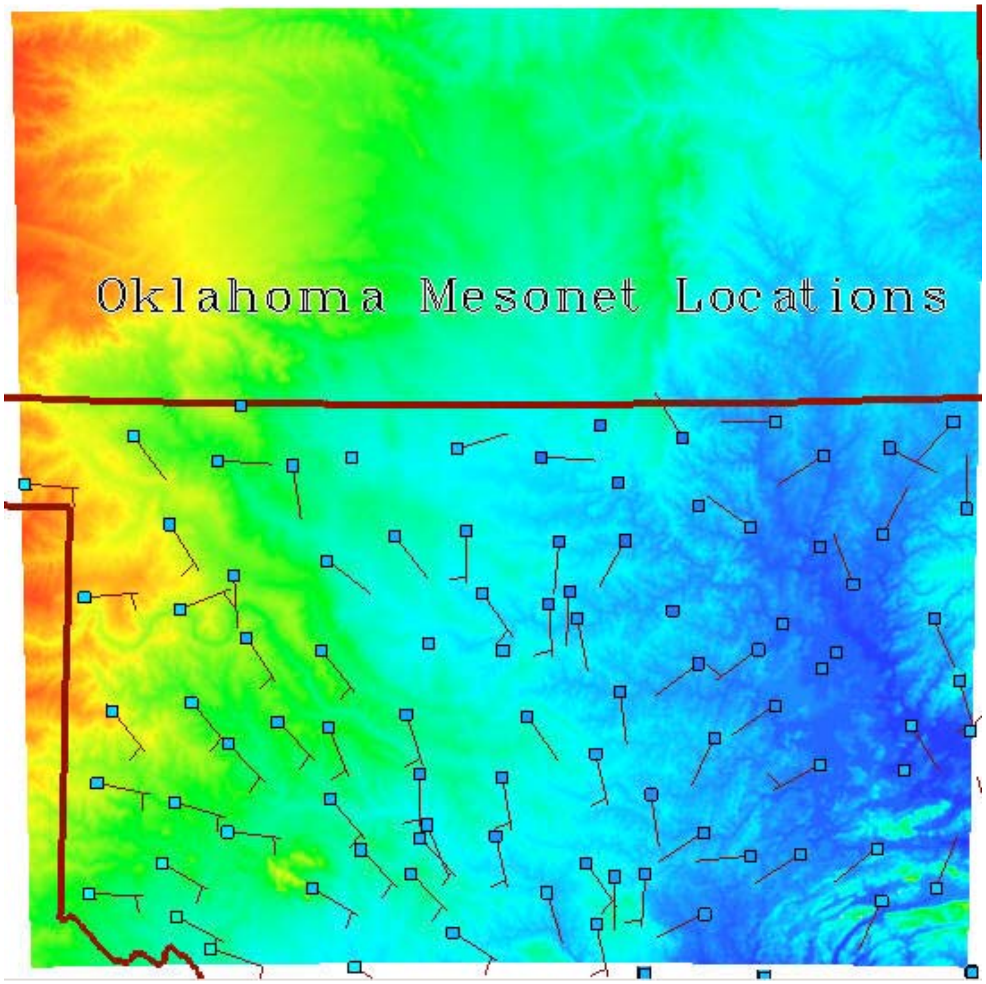
STATSGO = USDA State Soils Geographic Database

FAO = UN Food and Agricultural Organization

GDAS = NCEP Global Data Assimilation System

NCEP = National Centers for Environmental Prediction

Spin-Up Domain and Mesonet Stations

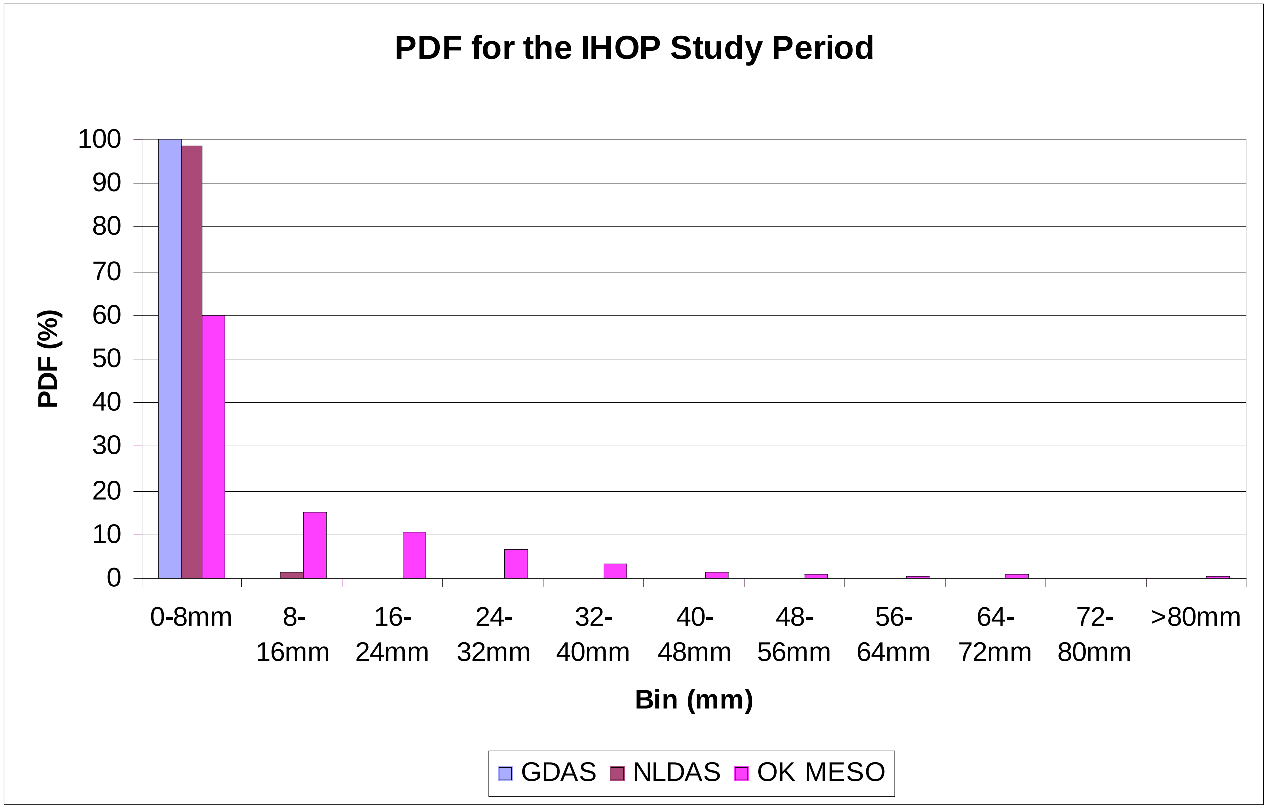


- 500x500 Horizontal Grid Points
- Integrations ran for 15 years ending June 26, 2002
- Forcing Evaluated against the Oklahoma mesonet for the period May 1st through June 12th, 2002
- Nearly 190,000 observations processed

GDAS and NLDAS Performance Statistics

Variable	RMSE GDAS	RMSE NLDAS	BIAS GDAS	BIAS NLDAS	Mesonet Average	GDAS Average	NLDAS Average	r GDAS	r NLDAS
Mixing Ratio (g/kg at 2m)	1.98	2.16	-1.09	-1.79	13.99	12.90	12.20	0.90	0.95
Temperature (C at 2m)	1.78	2.10	-0.06	1.02	21.45	21.50	22.47	0.92	0.96
Wind Speed (m/s at 10m)	1.75	1.85	-0.14	0.47	4.48	4.33	4.95	0.75	0.76
Pressure (mb)	4.48	3.23	-0.55	0.64	973.10	972.55	973.74	0.96	0.98
Precipitation (mm)	5.75	2.60	-0.36	0.12	1.95	1.59	2.07	0.61	0.93
Net Radiation (W/m2)	133.7	79.86	16.90	17.26	255.04	271.94	272.30	0.92	0.94

Precipitation Forcing



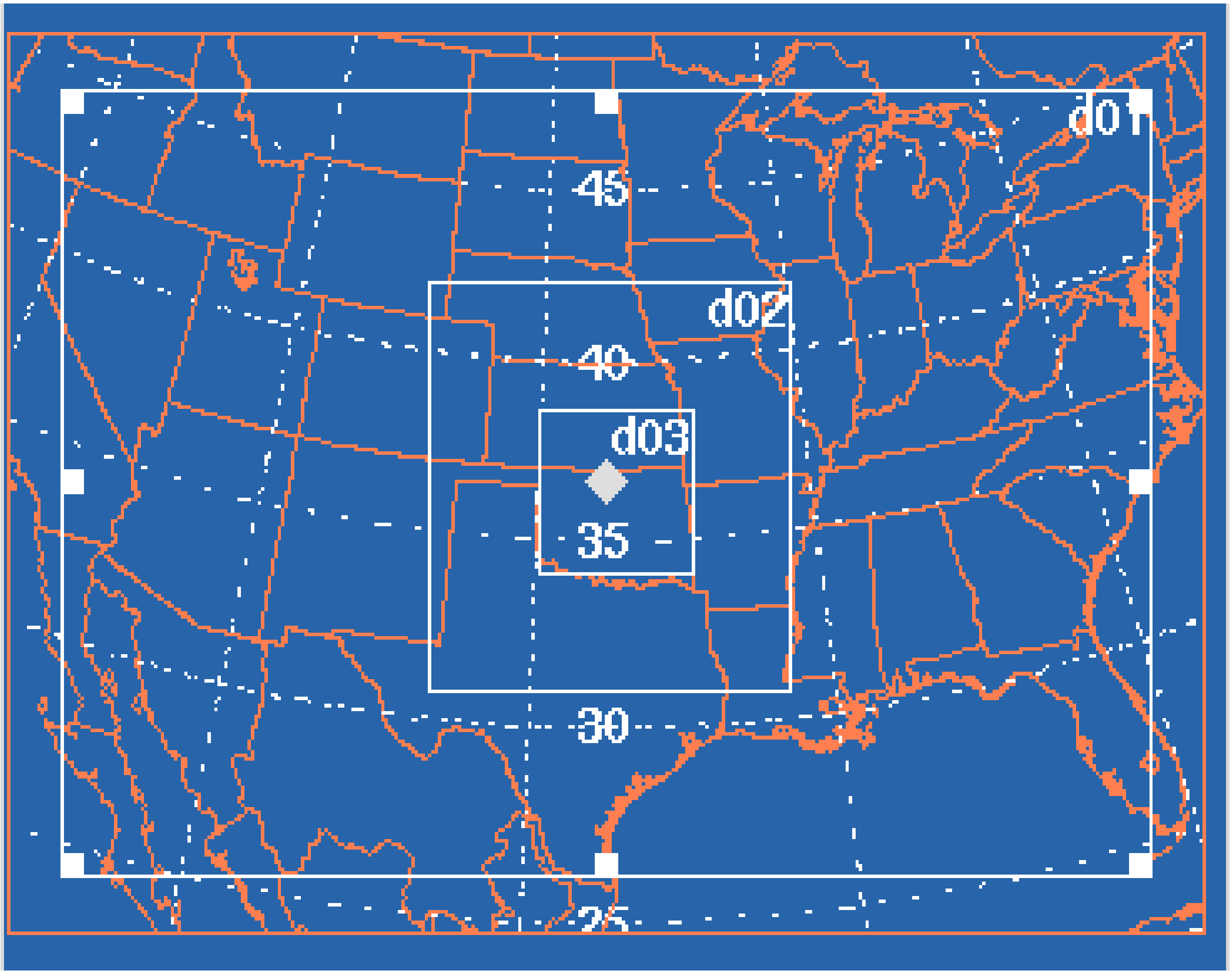
- Lack of moderate to heavy precipitation is clear without the proper rainfall forcing the benefit of NLDAS is minimized

- Stage IV 4km resolution is nearly implemented

Other Findings from Spin-Up Evaluation

- GDAS forcing lacked the temporal resolution to simulate rapid diurnal changes in surface fluxes of latent and sensible heat
- Increased soil data resolution led to a strong correlation with the observed variance in soil temperature and moisture
- The NOAH soil model exhibited large diurnal variations in temperature and moisture throughout the depth of the soil column

Application of Spin-Ups and Nesting to a Case Day

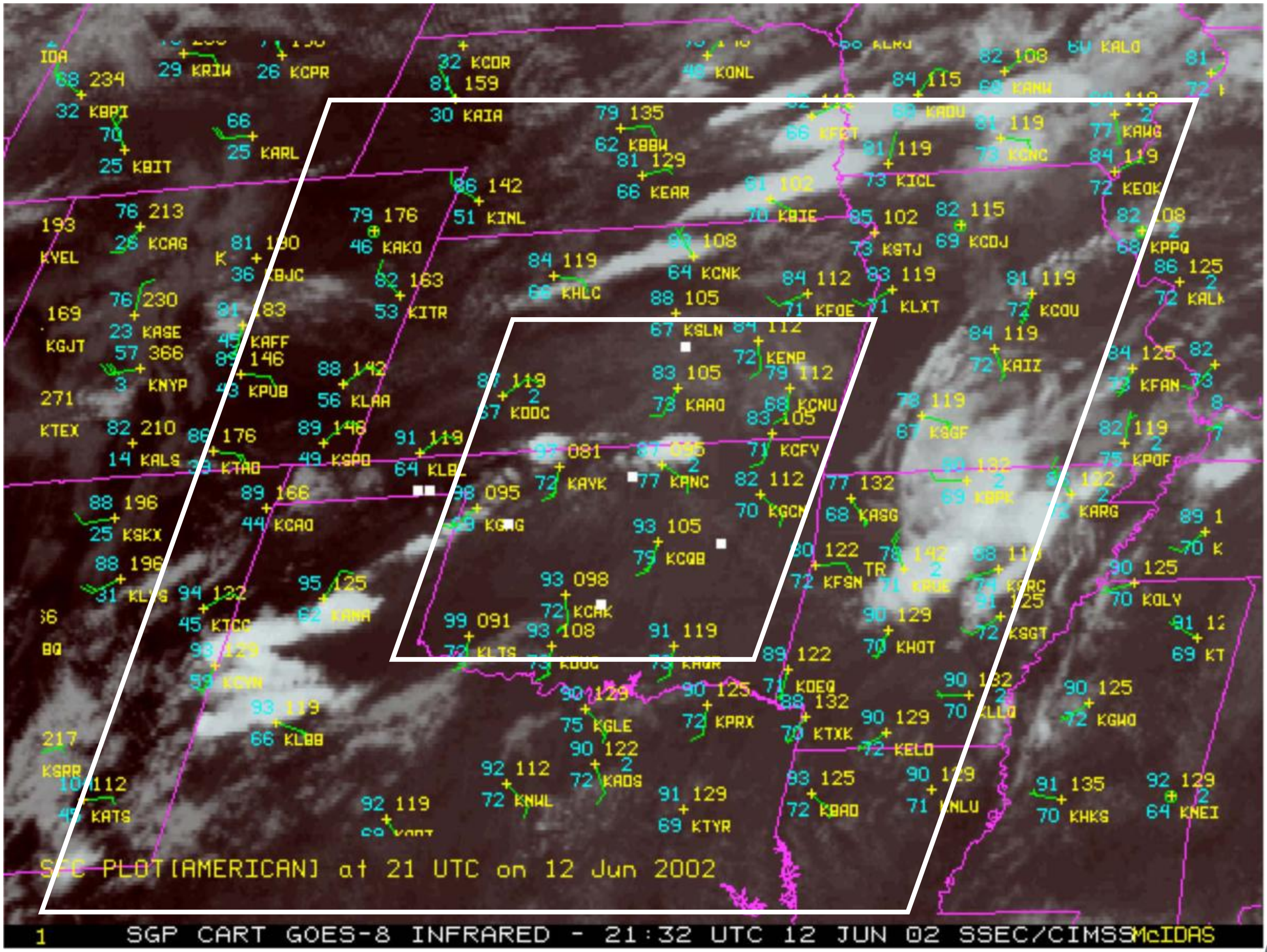


Configuration of the triple nested domain used in the coupled LIS-WRF simulations

The Case Day - June 12th, 2002

- **Employing the IHOP analysis of Grams et al., 2004 a case day, June 12-13th, 2002 was selected that displayed Discontinuous Areal (DA) properties in the CRA analysis**
- **The convection for this day was broken, and exhibited back-building**
- **The day also represented a mesoscale modelers' "Golden Day" properties; light winds and generally clear skies until the onset of convection**

The Onset of Convection, June 12, 2002 at 2130GMT



Summary of Coupled LISWRF Integrations

All used the NOAH LSM

3 Nested integrations using LIS spin-Ups and WRSI requiring 50Gb RAM and 150Gb of storage:

- NLDAS forcing+STATSGO Soil+Lin Microphysics
- NLDAS forcing+STATSGO Soil+GCE Microphysics
- WRFSI

5 Non-nested integrations using various forcing/parameter data:

Simulation Symbol	Forcing	Forcing Resolution	Soils	Soil Resolution
WRFSI	N/A	N/A	N/A	N/A
F0	GDAS	2.5 degree, 3 hour	FAO	5 minute
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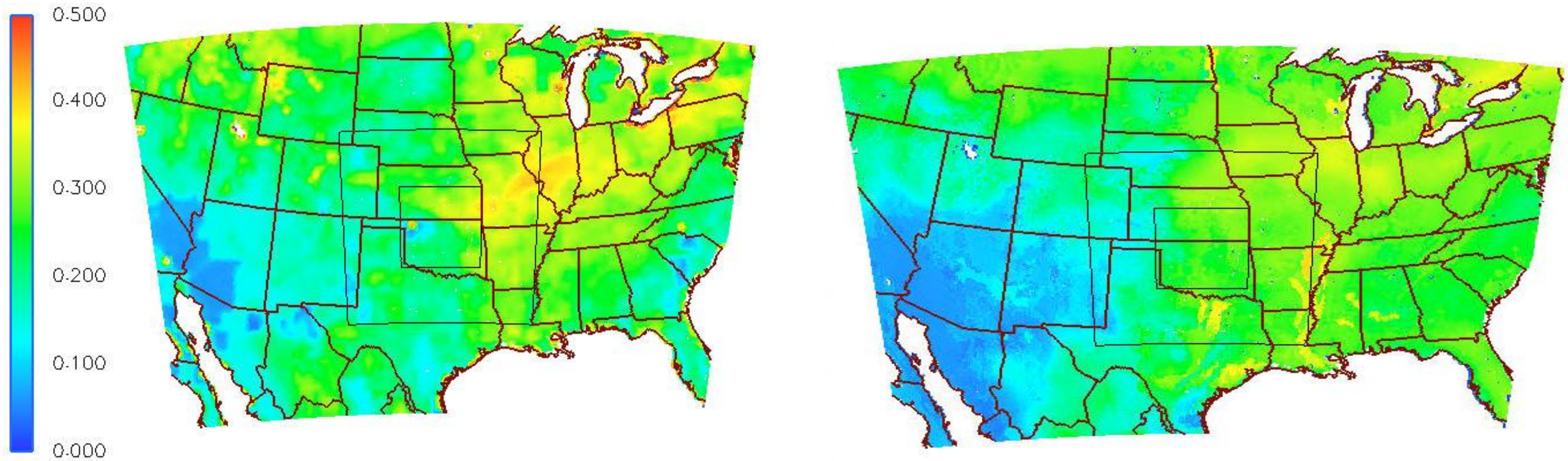
Soil Moisture 10cm, 9km nest
June 12, 2002

WRFSI LIS Spinup



Domain consisted of a 9km mesh with 400x271 horizontal points with a 3km inner nest with 403x403 points, and a 1km mesh with 505x505 grid points. All grids had 45 vertical levels from the surface up to 20km

Non-nested domains only employed the inner mesh

LIS Spinup = 17 years starting from 1985 using bias-corrected atmospheric reanalysis data until 2000. From 2000 onwards inner nests forcing data was NLDAS (GOES radiation & Stage IV precipitation), outer nest data from GDAS (NCEP Global Data Assimilation System).

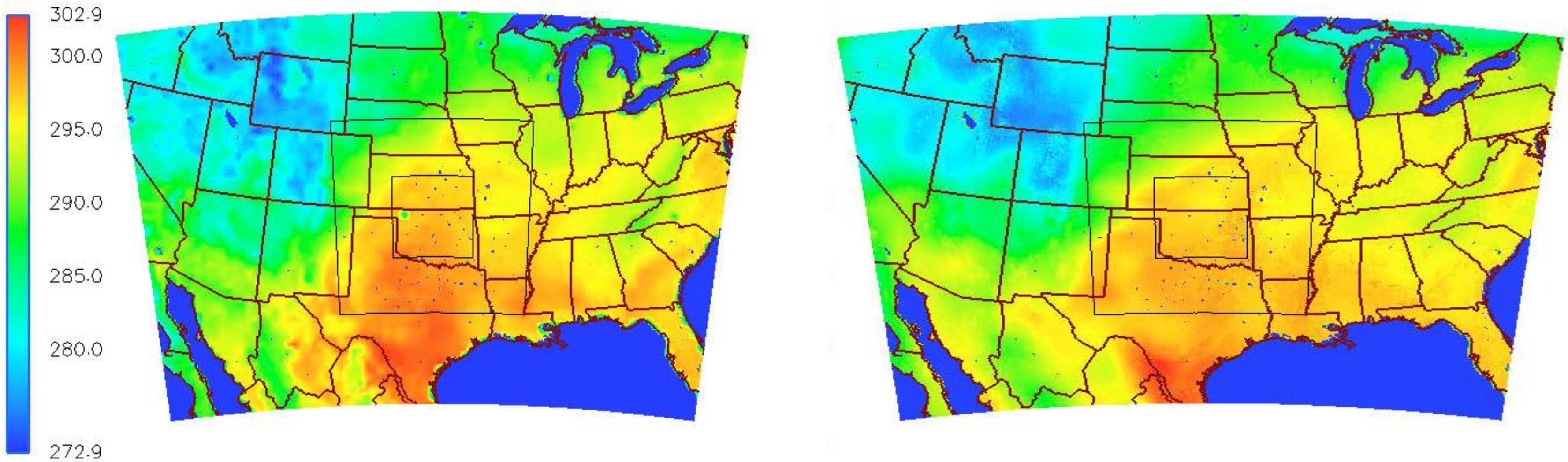
1 km global vegetation from University of Maryland for vegetation-based parameters in Noah.

Soil hydraulic properties from Food and Agricultural Organization (FAO) database for outer nest, 1 km State Soil Geographic Database (STATSGO) soils database for inner nests.

Soil Temperature 10cm, 9km nest
June 12, 2002

WRFSI

LIS Spinup



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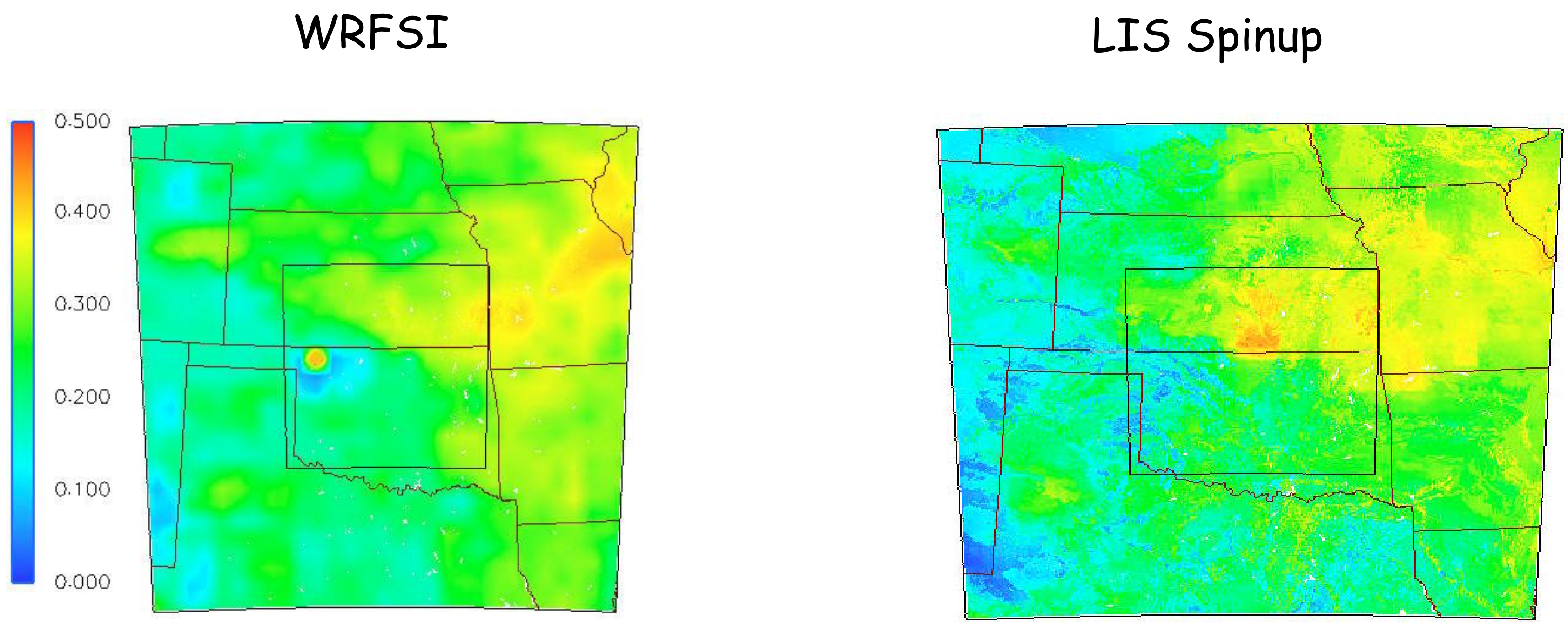
Soil Moisture 10cm, 3km nest June 12, 2002



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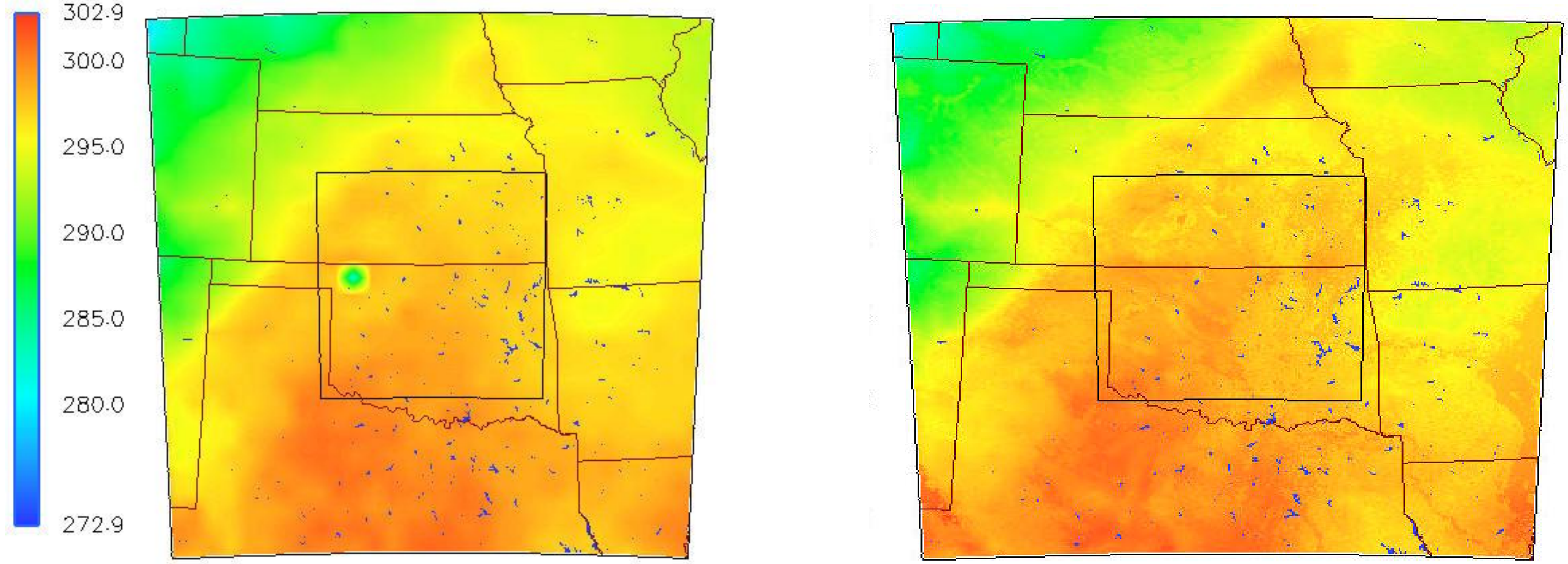
Soil Temperature 10cm, 3km nest
June 12, 2002

WRFSI | LIS Spinup



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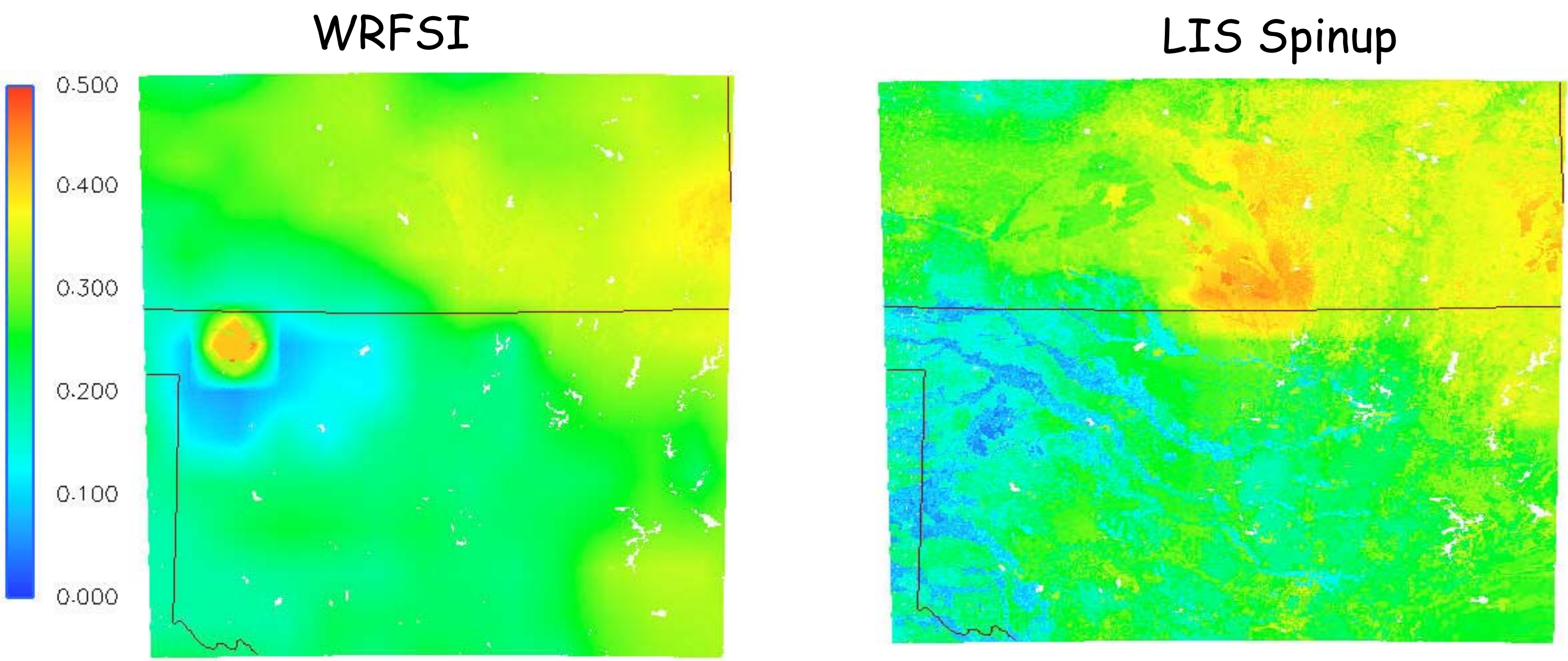
Soil Moisture 10cm, 1km nest
June 12, 2002



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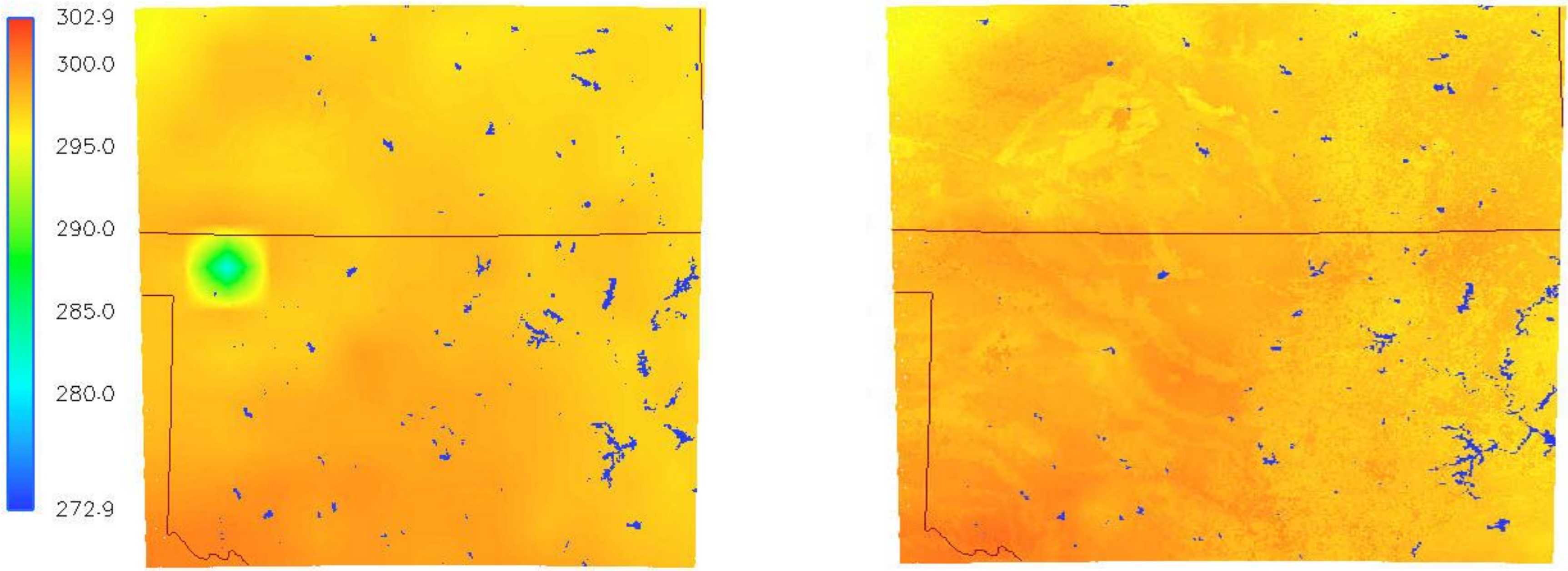
Soil Temperature 10cm, 1km nest
June 12, 2002

WRFSI LIS Spinup



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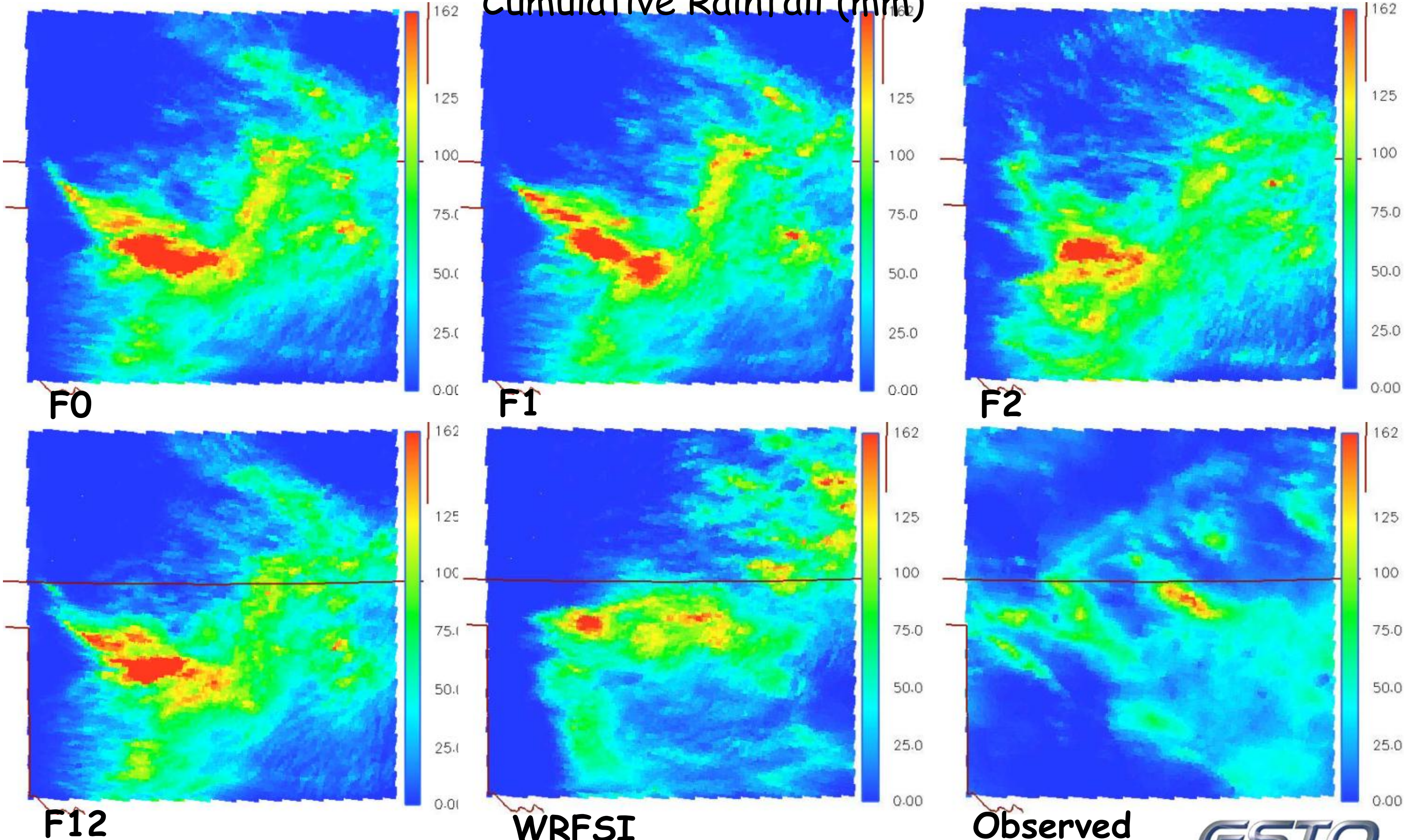
Effect of LIS (Non-Nested Domain) on PRCP FCST, June 12, 2002

Cumulative Rainfall (mm)



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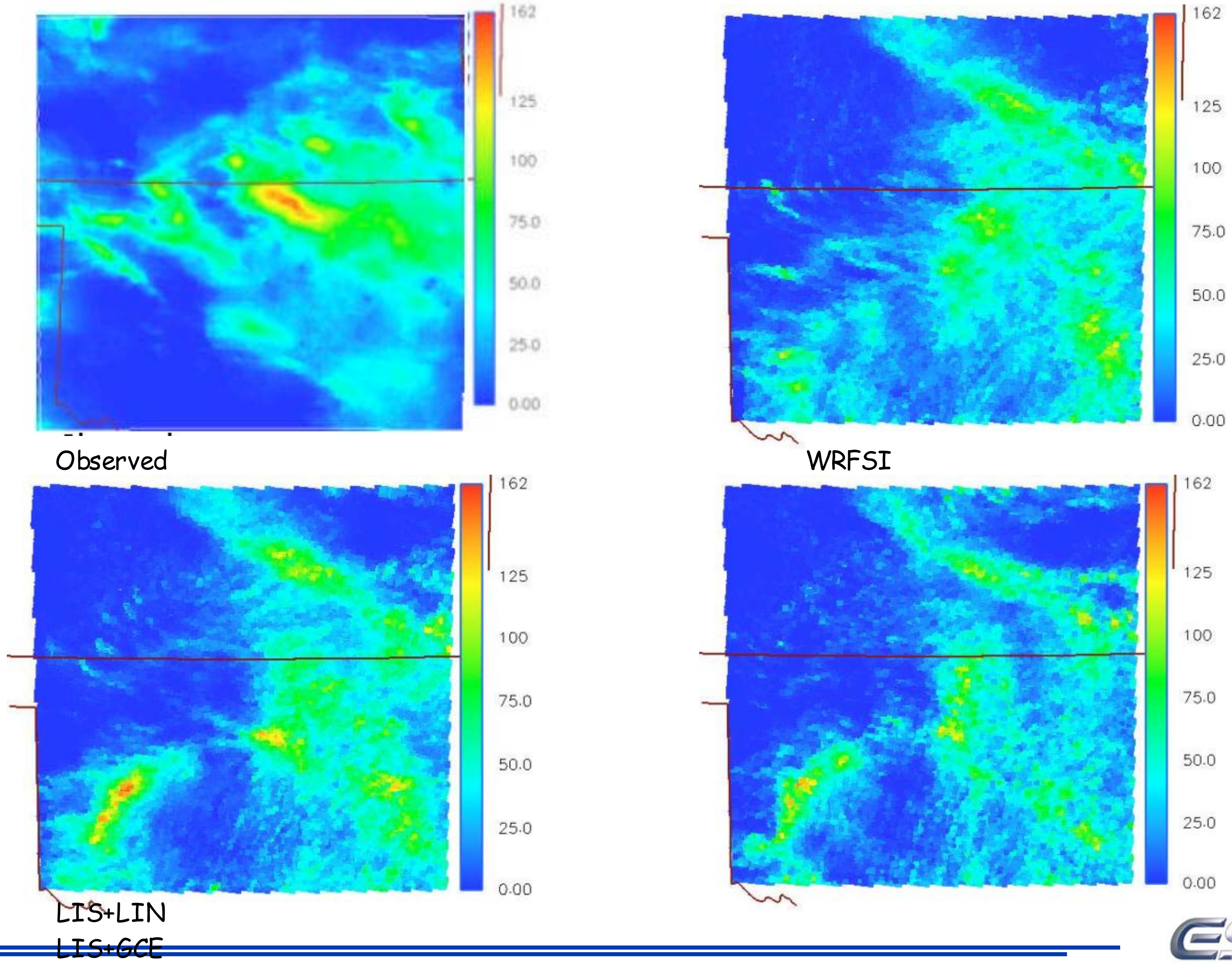
Effect of LIS (Nested Domain) on PRCP FCST, June 12, 2002



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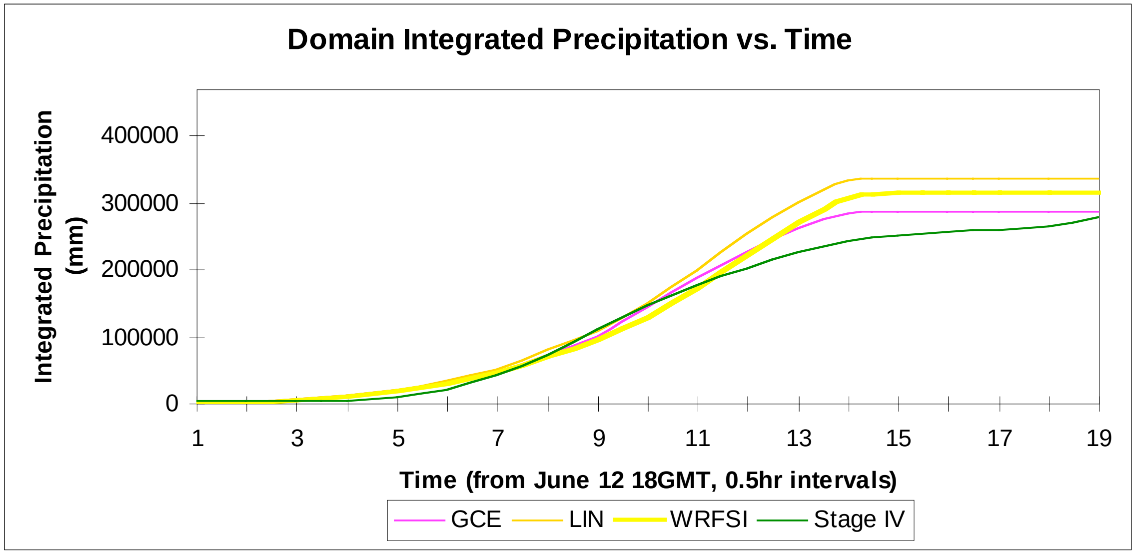
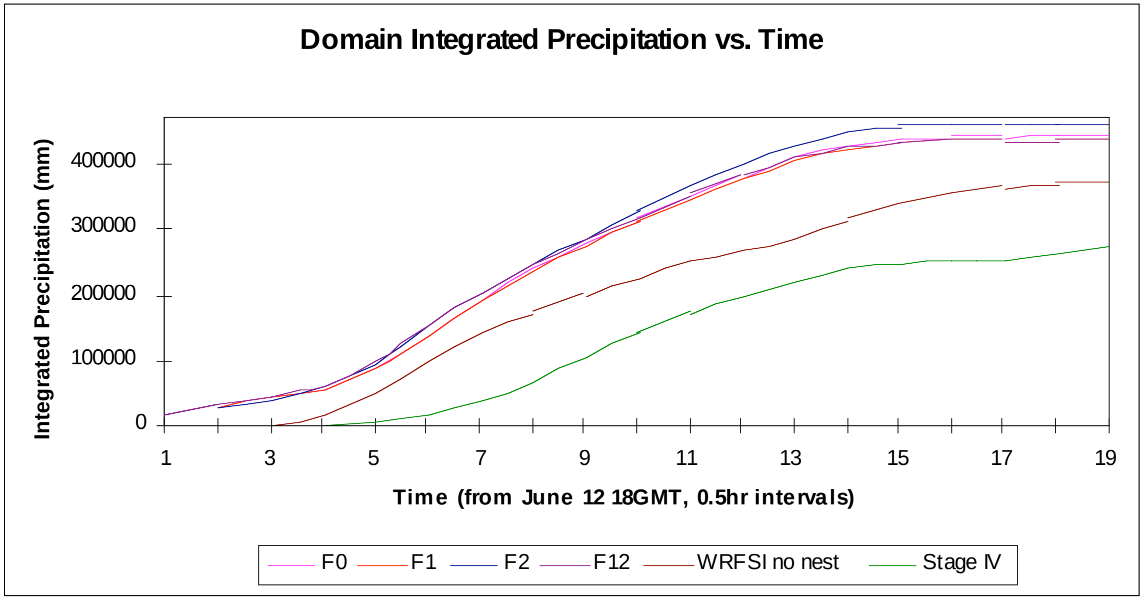
Integrated Precipitation Comparison (June 12, 2002)

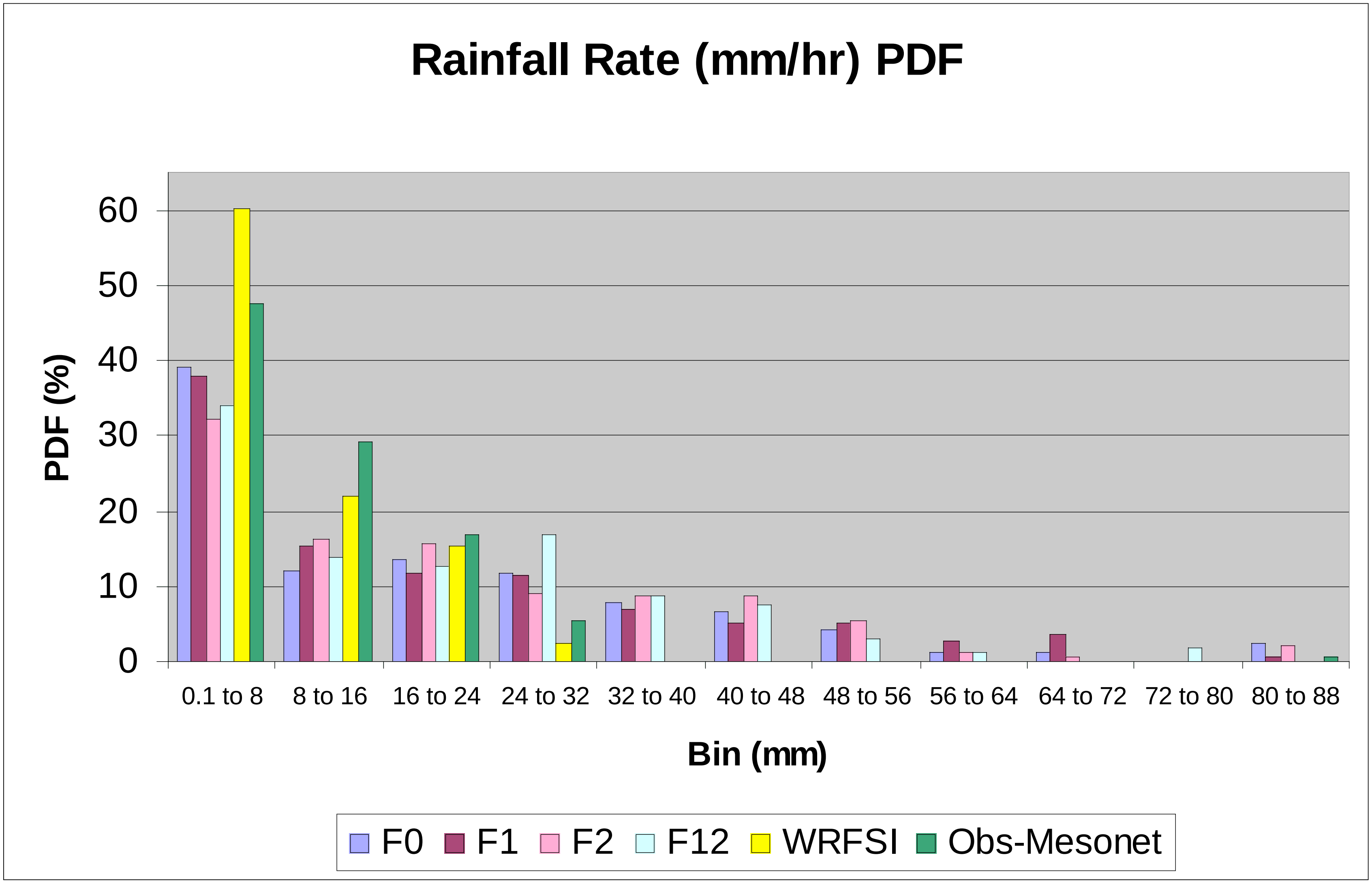
Nested Domain



Non-Nested Domain



Rain Rate PDF Non-Nested Domain (June 12, 2002)



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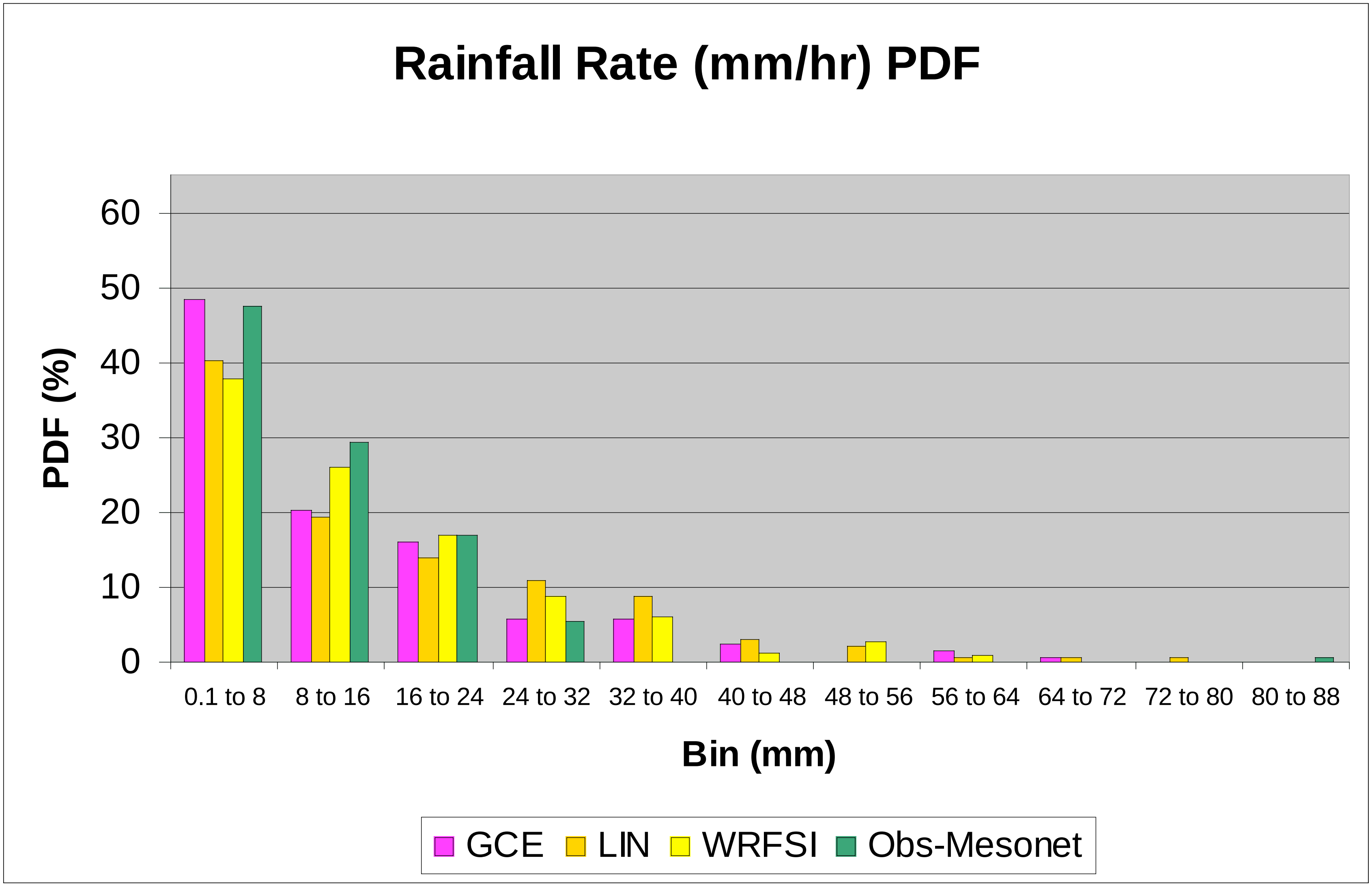
Rain Rate PDF Nested Domain (June 12, 2002)



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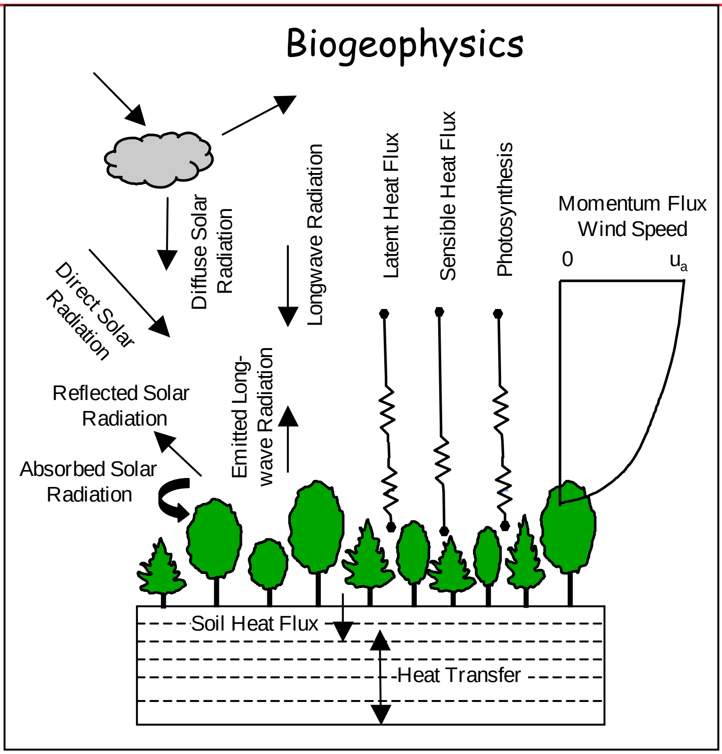
Conclusions from Integrations and Spin-Up Evaluation

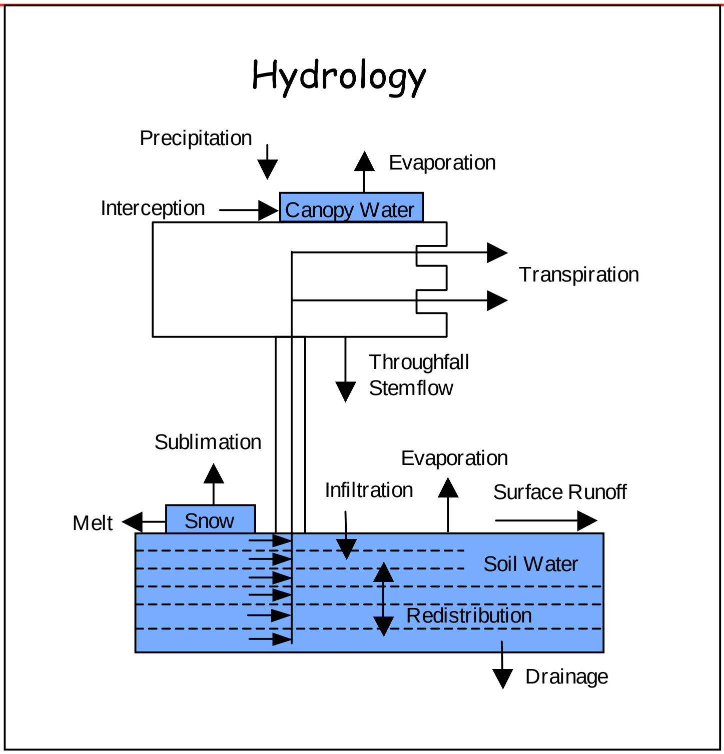
- Precipitation forcing needs increased resolution for high resolution spin-ups
- The NOAH LSM seems rather insensitive to initial soil conditions
- The GCE microphysics results show better agreement with observations in the nested simulations
- LIN microphysics showed a tendency to over-predict precipitation in the spin-up integrations. Analysis suggests this is a result of the drier and hotter soil conditions causing convective temperature to be reached earlier
- The nesting improves the temporal agreement with the observations. It was found that this was due to a fairly deep upper level trough that was moving into the finer meshes influencing the cloud layer mean wind by adding a westerly component
- NOAH greenness fraction has a 1 degree resolution and vegetation dominates the soils

Can we get the right answer?

- Final set of Spin-Ups were conducted using NLDAS+STATSGO+AVHRR for the NOAH and CLM2 LSMs
- Again, these were evaluated against the OK Mesonet
- CLM2 reduced simulated temperatures biases by a factor of 2, soil moisture bias by a factor of 3
- Soil Temperature Correlation Coefficients increased from 0.70 to 0.80 at 10cm, and from 0.45 to 0.64 at 30cm depths
- Soil Moisture Correlations increased from 0.45 to 0.64 at 10cm, 0.44 to 0.69 at 25cm, and 0.39 to 0.68 at 75cm

Community Land Model





CLM simulates energy and moisture exchanges between land and atmosphere

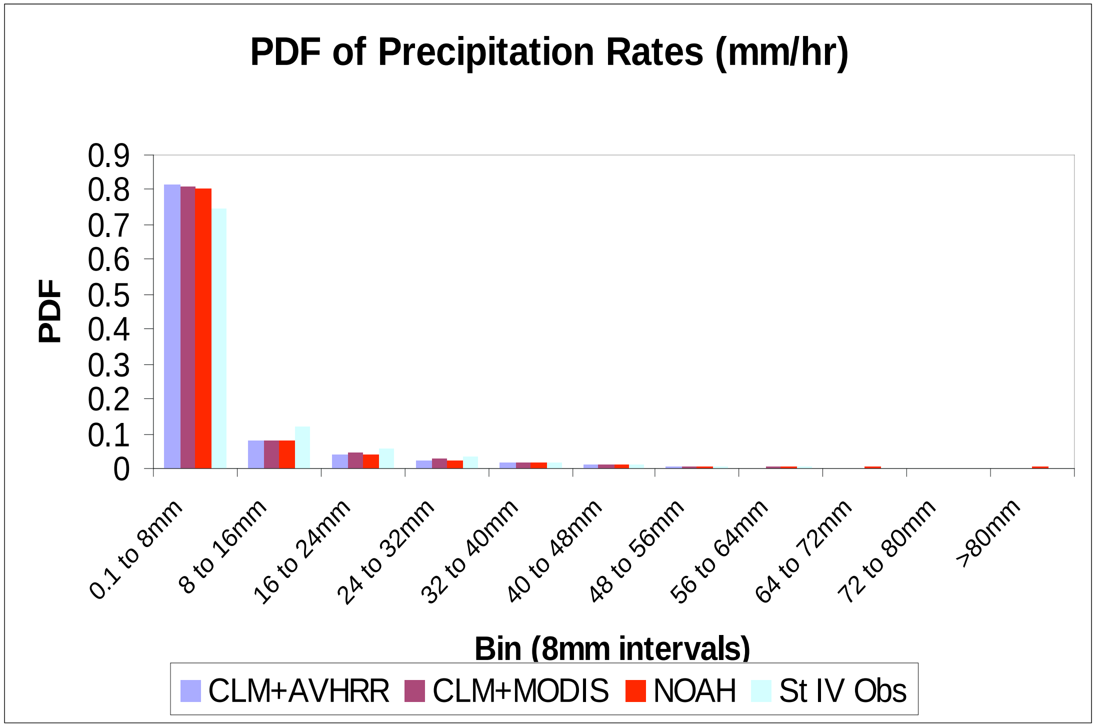
Energy exchanges include radiative transfer, turbulent fluxes, and heat storage in soil

These are controlled in part by the hydrologic cycle

CLM has a detailed representation of the hydrologic cycle including: interception of water by leaves; infiltration and runoff; multi-layer snow accumulation and melt; 10-layer soil water; and partitioning of latent heat into evaporation of intercepted water, soil evaporation, and transpiration

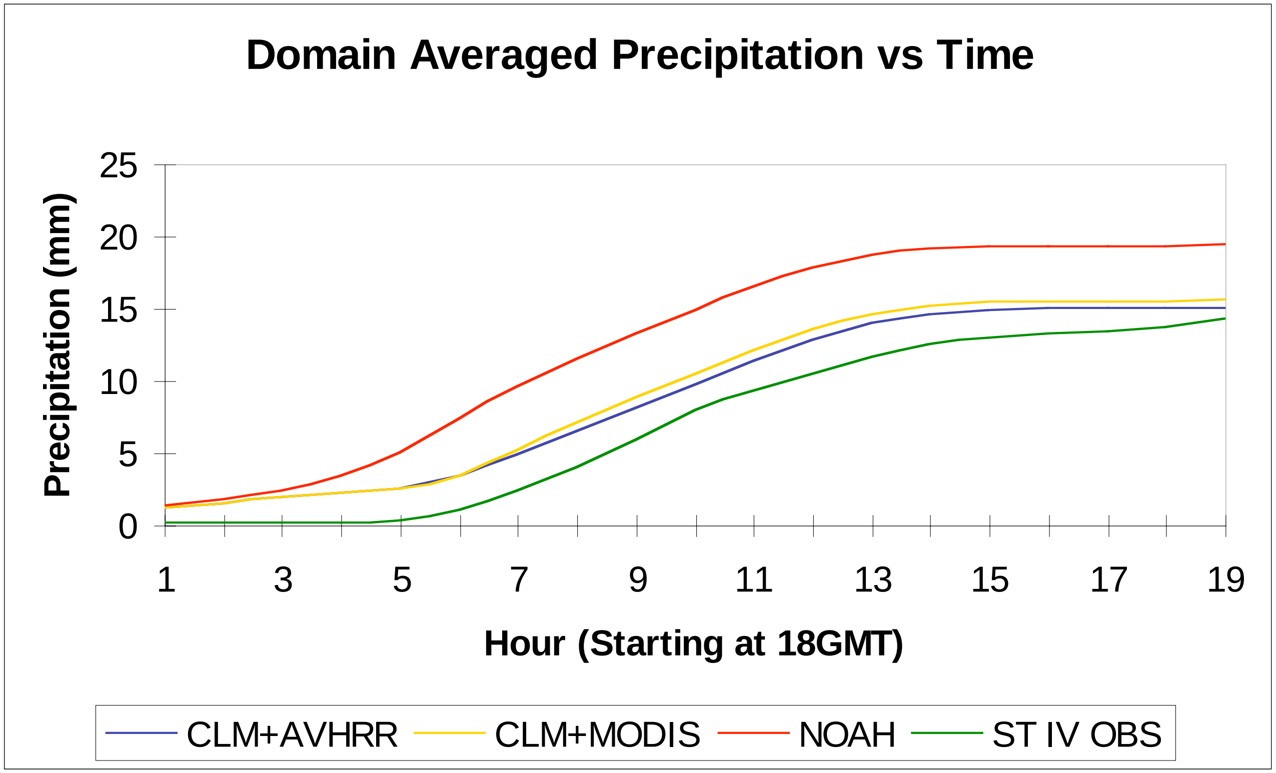
Bonan (2002) Ecological Climatology (Cambridge University Press)

Now we can begin to answer whether better spin-ups produce better coupled integration results



- *The distributions are quite similar and show excellent agreement with observations over all bins*
- *NOAH largely over-predicts at heavy precipitation rates*

Comparison of CLM and NOAH



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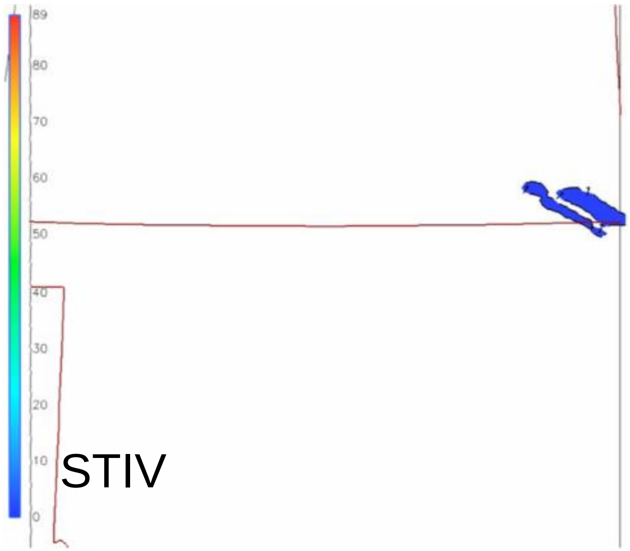
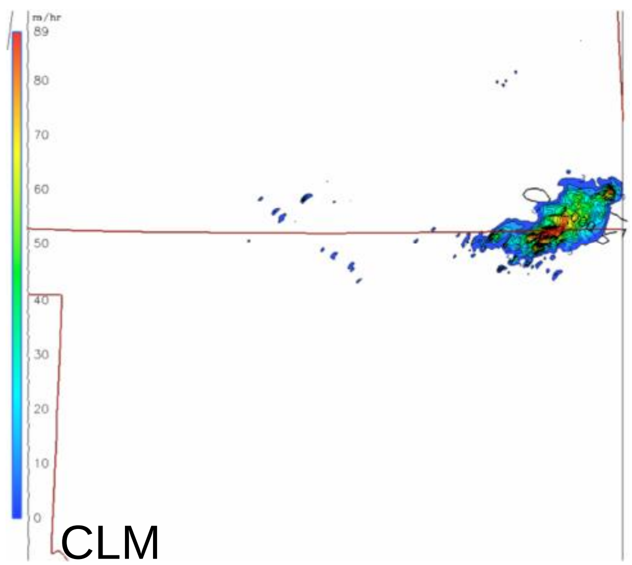
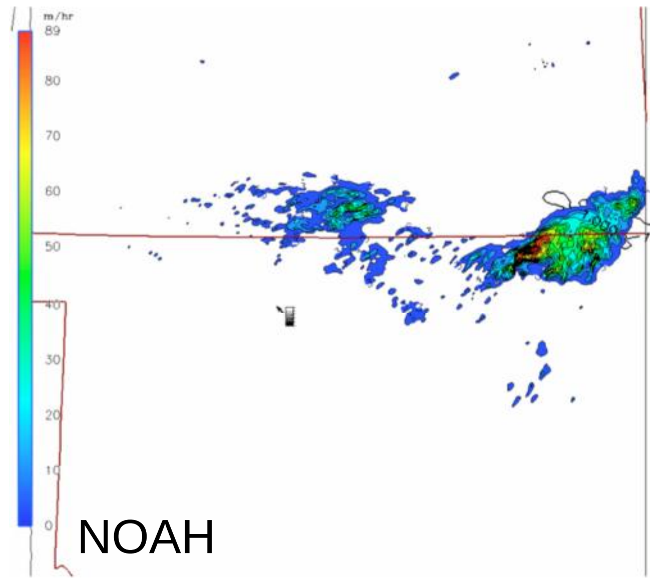
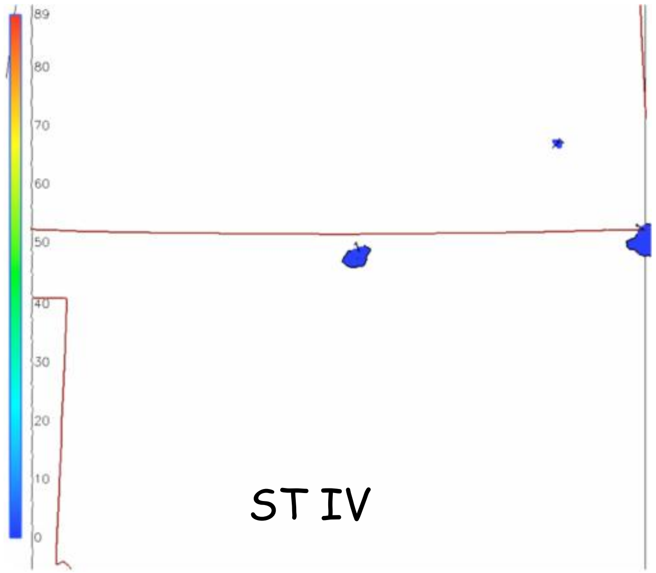


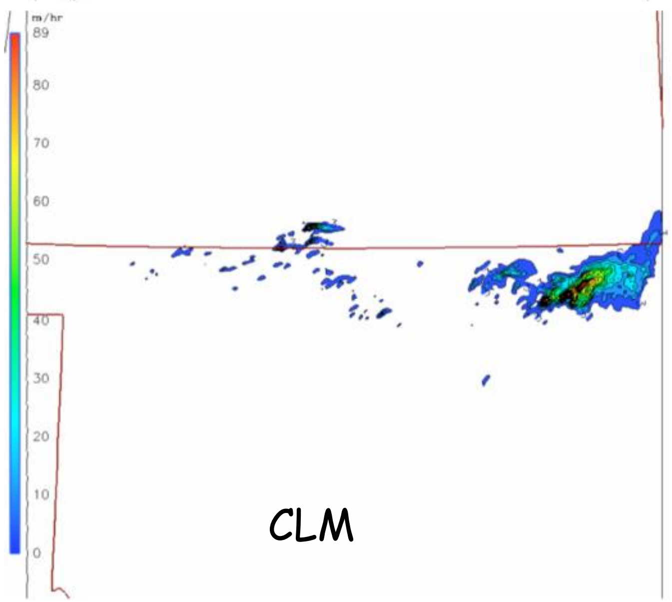


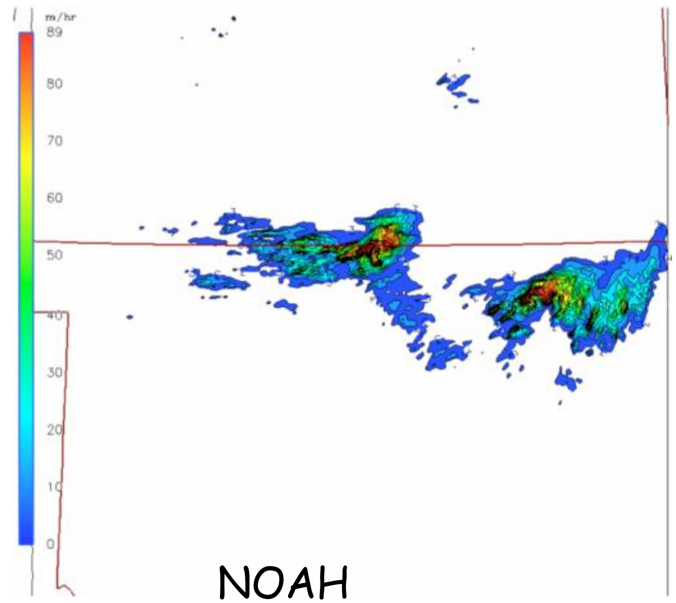


Precipitation Rates (mm/hr) at 20GMT

Comparison of CLM and NOAH

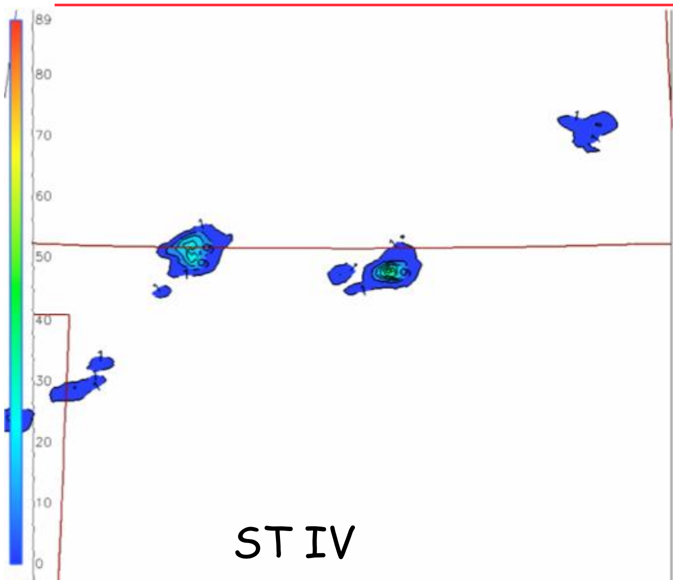


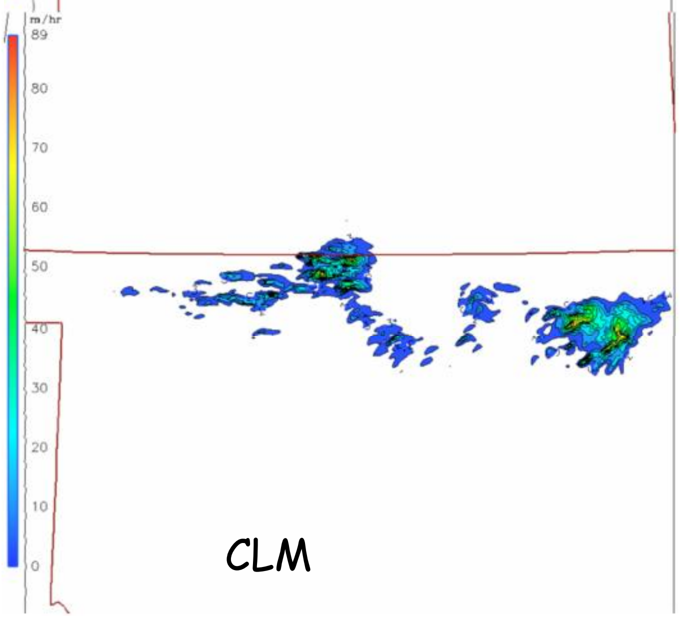


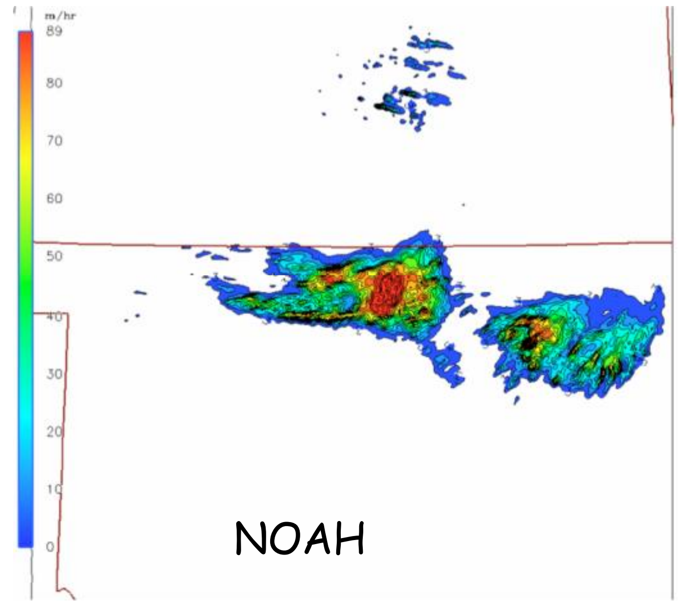


Precipitation Rates (mm/hr) at 21GMT

Comparison of CLM and NOAH

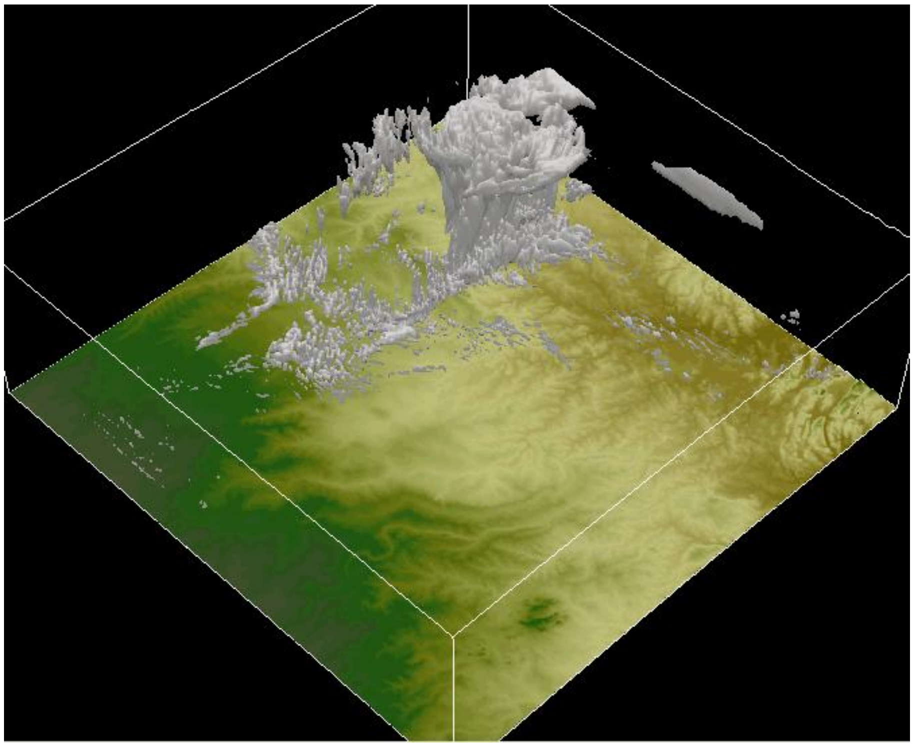


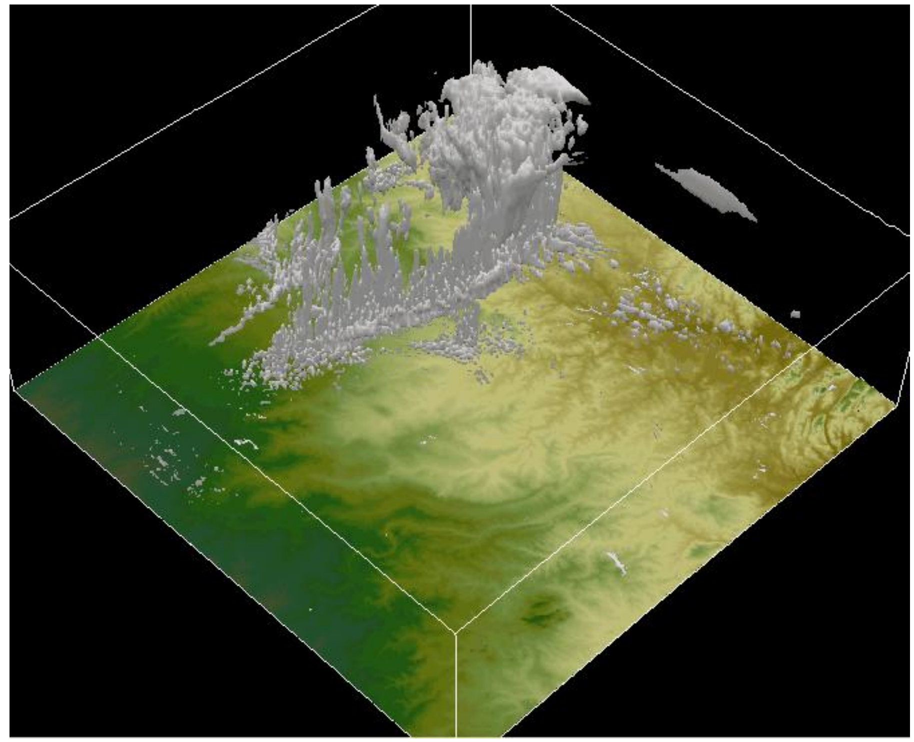




Same as before at 22GMT

What does this look like?





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CLM and NOAH Comparison

- A detailed analysis of the Moisture Flux Convergence indicates that the CLM model produced temporal and spatial location of maxmima consistent with the observations
- These locations were coincident with related to the partitioning of the surface energy budget and the latent, sensible, and ground heat flux partitioning
- Drier and hotter soil moisture states led to NOAH integrations realizing earlier convective temperatures, producing an earlier and stronger onset of convection

Conclusions

- Do the initial lower boundary conditions from Land Surface Model (LSM) spin-ups enhance the modeling of convection?

The results indicate this is dependent on the LSM employed in the integration

- Does higher resolution forcing employed in the spin-up integrations improve the integration results ?

This was found to be inconclusive. We believe that the incorporation of hi-res precipitation forcing will add to the ability of Spin-Up integrations to improve predictibility

- Do different LSMs have an impact on the model's ability to simulate convection?

In this case it does.

- Does the addition of higher resolution parameter data enhance the predictability?

In the case of NOAH and hi-res soils cases this was not the case. When the CLM LSM was used in conjunction with AVHRR and MODIS derived LAI slight improvements were seen. As previously mentioned hi-res precipitation could potentially enhance the effects of parameter resolution.

More Conclusions and Follow-On Recommendations

Conclusions

- LIS has been successfully coupled to two atmospheric model components, WRF and GCE.
- The coupling adds minimal computational overhead.
- The coupled system allows scientists to study the impact of input data, microphysical and radiative transfer processes, and boundary conditions on water and energy cycles.

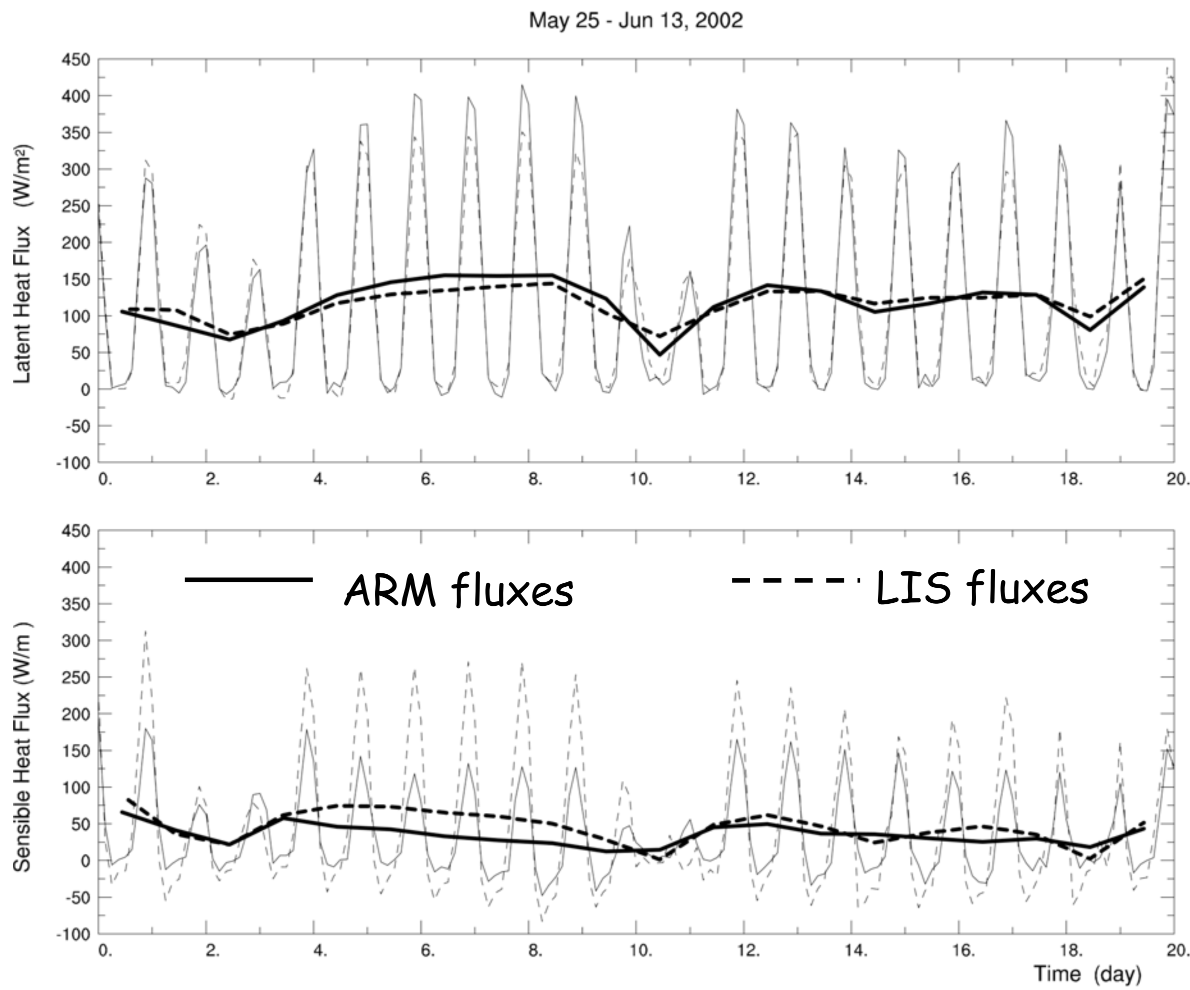
Follow-On Recommendations

- Advancement to TRL7 would be the equivalent of using WRF-LIS pseudo-operationally. To continue this advancement would require an integrated 3-5 year project involving several organizations involved in LIS/WRF/GCE and ESMF:
    - E.g., GSFC, NOAA/NCEP, National Center for Atmospheric Research, Air Force Weather Agency

Long Term GCE Results
Surface Fluxes of May 25-Jun 13, 2002

Zeng et al., JAS, 2006

ARM surface fluxes (solid) LIS fluxes (dashed lines). Thick lines represent daily average values for no diurnal variation.



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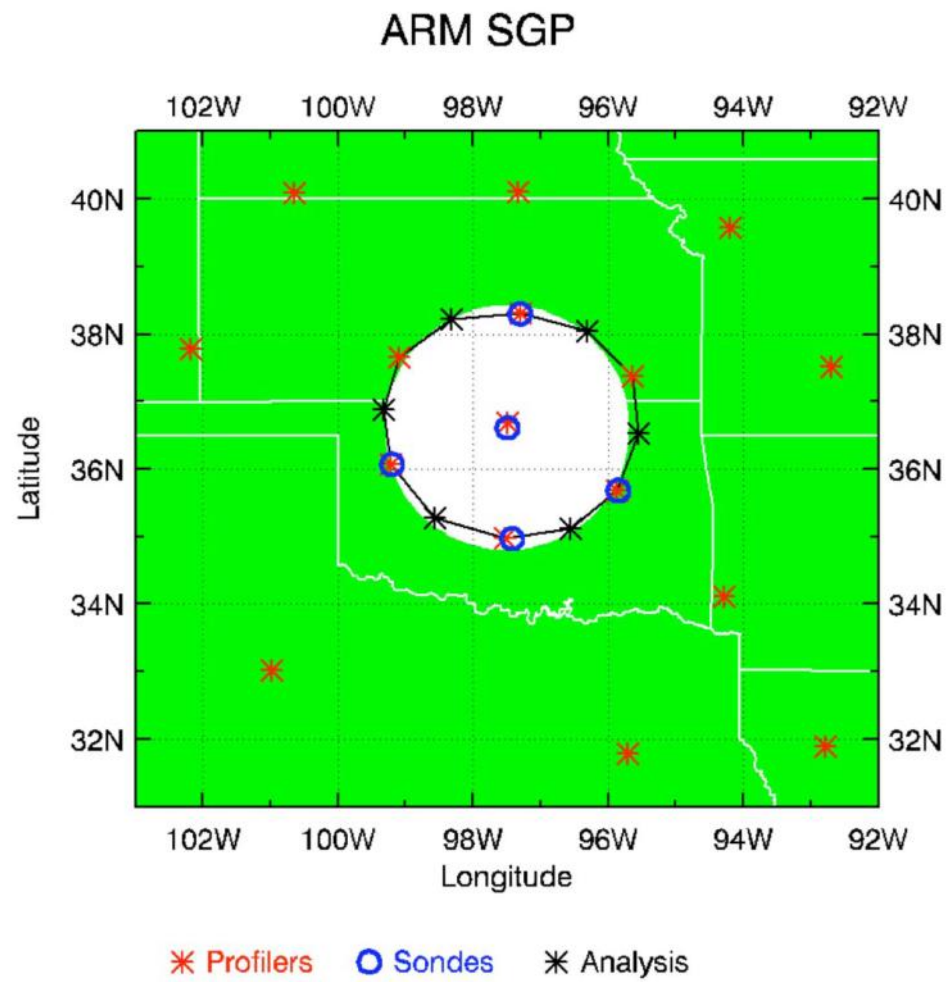
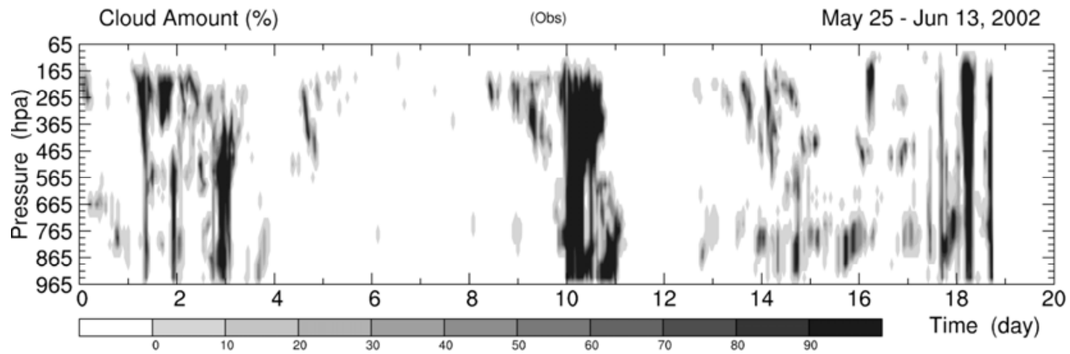
IHOP Long Term GCE Results
Center: (36.61N, 97.49W) Radius: 1.82°

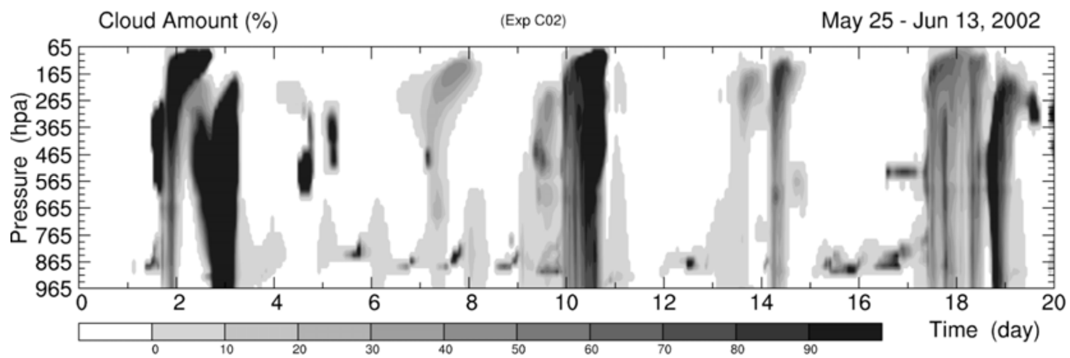


Long Term GCE Results
Cloud Fraction Evaluation

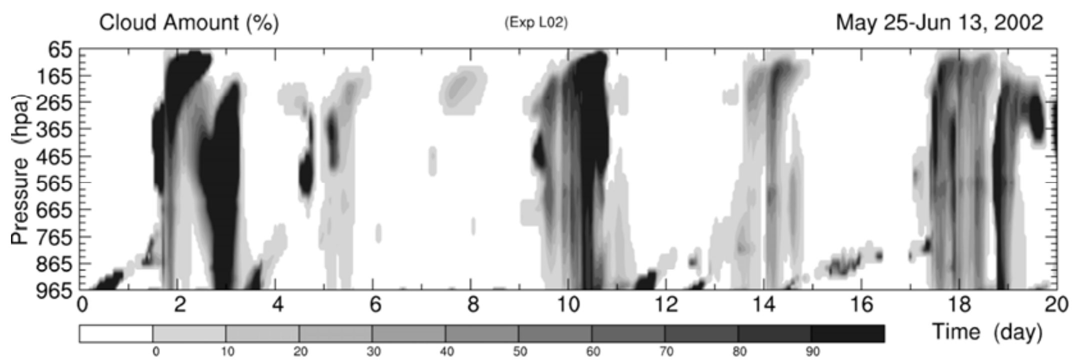
Observed



GCE - ARM



GCE - LIS



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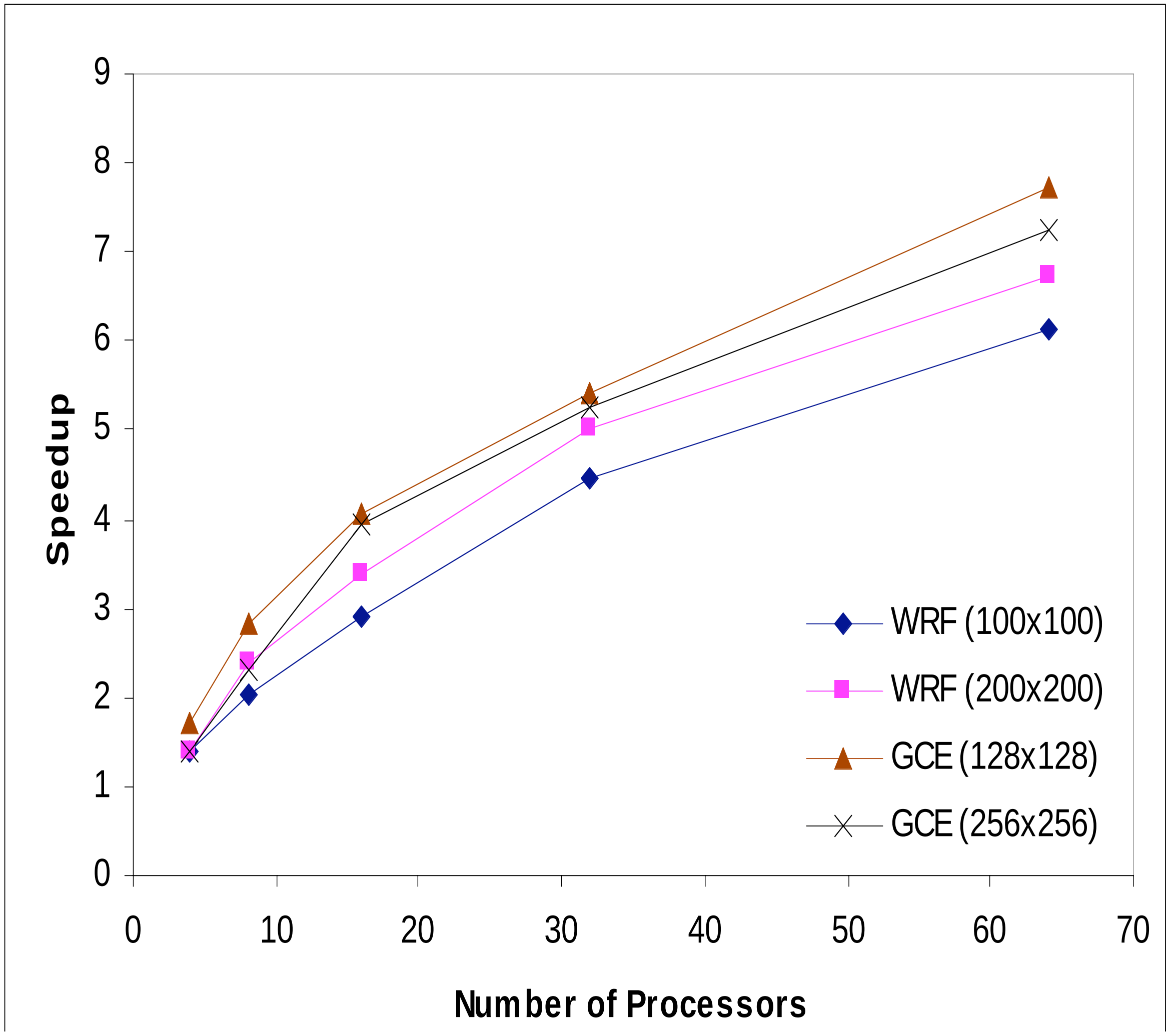
Performance Measures: WRF/LIS and WRF/GCE
Performance scaling for the coupled systems



Project Publications

Conference Papers

- Peters-Lidard, Christa, Sujay Kumar, Wei-Kuo Tao, Joseph Eastman, Xiping Zeng, Steve Lang, and Paul Houser, 2005: Coupling High Resolution Earth System Models Using Advanced Computational Technologies, Earth-Sun Technology Conference, June 28-30, 2005, College Park, MD.
- Kumar, S. V., C.D. Peters-Lidard, J.L. Eastman, and P.R. Houser, 2005:. High Resolution coupled land-atmosphere system using the Land Information System and Weather Research and Forecasting model enabled by ESMF, WRF/MM5 User's Workshop, June 27-30, 2005, Boulder, CO.
- Eastman, J. L., Christa Peters-Lidard, S. Kumar, and Y. Tian, 2005: Hi-Resolution Convective Modeling Study using WRF Coupled to the Land Information System, WRF/MM5 User's Workshop, June 27-30, 2005, Boulder, CO.
- Eastman, J. L., Christa Peters-Lidard, S. Kumar, and Y. Tian, 2005: Evaluation of land surface spin-up and their impacts on hi-resolution convective modeling, 86th Annual AMS meeting, January 29th through February 2nd, 2006, Atlanta,GA.
- S. Lang, X. Zeng, W.-K. Tao, C. Peters-Lidard, J. Eastman, S. Kumar and Y. Tian, 2005 High-resolution CRM simulations from IHOP: Land-atmosphere interactions, 86th Annual AMS meeting, January 29th through February 2nd, 2006, Atlanta,GA.
- Sujay Kumar, Christa Peters-Lidard, Joseph Eastman, Yudong Tian, Paul Houser, 2005: Evaluation of the impact of land surface heterogeneity representations on mesoscale fluxes, 86th Annual AMS meeting, January 29th through February 2nd, 2006, Atlanta,GA.
- Sujay Kumar, Christa Peters-Lidard, Wei-Kuo Tao, Yudong Tian, Joseph Eastman, Xiping Zeng, Steve Lang and Paul Houser, 2005: Advanced computing, data access and distribution

Project Publications

Conference Papers (continued)

- Xiping Zeng, W-K Tao, M. Zhang, C. Peters-Lidard, S. Lang, J. Simpson, S. Kumar, S. Xie, J. L. Eastman, C-L Shie, and J. V. Geiger, 2006: Long-Term Numerical Simulations of Clouds in Contrast to ARM Observational Data, AGU Conference, May 23–26, 2006, Baltimore, MD.
- Joseph L. Eastman, C. Peters-Lidard, W-K Tao, S. Kumar, S. Lang, Y. Tian, and X. Zeng, 2006: The Impact of Forcing Resolution on Data Assimilation and High Resolution Atmospheric Modeling, AGU Conference, May 23–26, 2006, Baltimore, MD.
- Joseph L. Eastman, C. Peters-Lidard, W-K Tao, S. Kumar. X. Zeng, and S. Lang, 2006: Recent Accomplishments in Coupling High Resolution Earth System Models Using Advanced Computational Technologies, NASA's Sixth Annual Earth Science Technology Conference, June 27-29, 2006, College Park, MD.

Invited Talks

- C. D. Peters-Lidard, S. V. Kumar, Y. Tian, J. Geiger, M. Garcia, M. Rodell, P. R. Houser, E. F. Wood, J. Sheffield, K. Mitchell, J. Meng, P. Dirmeyer, B. Doty, and J. Adams, The production and value of high resolution land surface data assimilation products from the NASA/GSFC Land Information System, 5th International Scientific Conference on the Global Energy and Water Cycle, June 20-24, 2005 Costa Mesa, CA, USA.
- Joseph L. Eastman, Special thanks to C. D. Peters-Lidard, S. V. Kumar, and Y. Tian, Evaluation of land surface spin-up and their impacts on hi-resolution convective modeling, Goddard Earth Sciences and Technology (GEST) Seminar, April 5, 2006, University of Maryland Baltimore County, GEST Center, Baltimore, Maryland, USA.

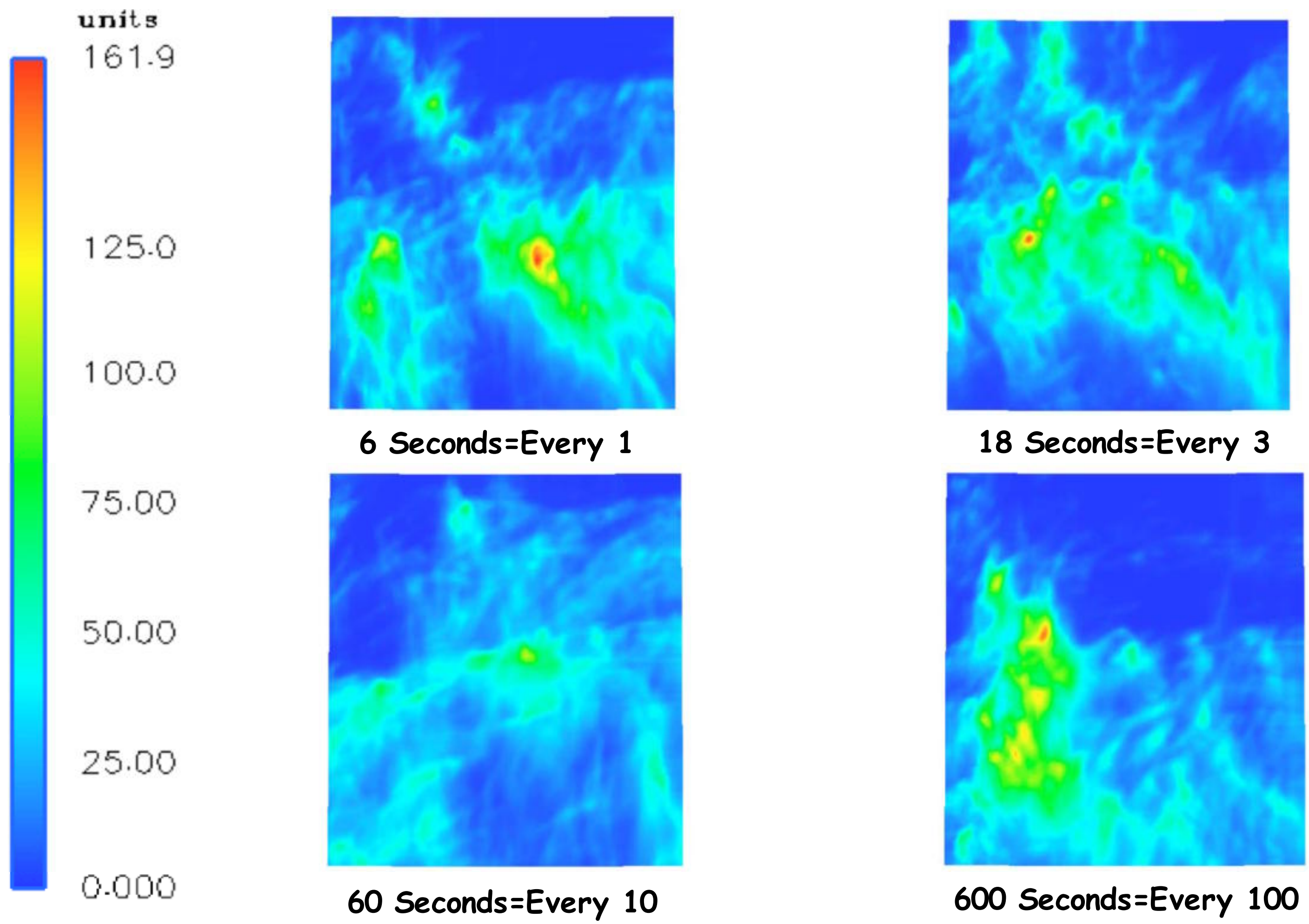
Radiation Coupling Time Step Experimental Design

In this experiment we employed the Weather Research and Forecasting (WRF) model coupled to the Land Information System (LIS) (LISWRF). A call to the radiation parameterization nearly triples the computational time required.

- Homogeneous initialization of meteorology for a DRY and WET case
- Noah Land Surface Model (LSM) with actual vegetation, homogeneous soil moisture/temperature
- 100x100x41 grid points at 1km spacing in the horizontal and stretched in the vertical with a time step of 6s
- Four 24 hour integrations for each WET/DRY case with radiation called every 6, 18, 60, and 600s

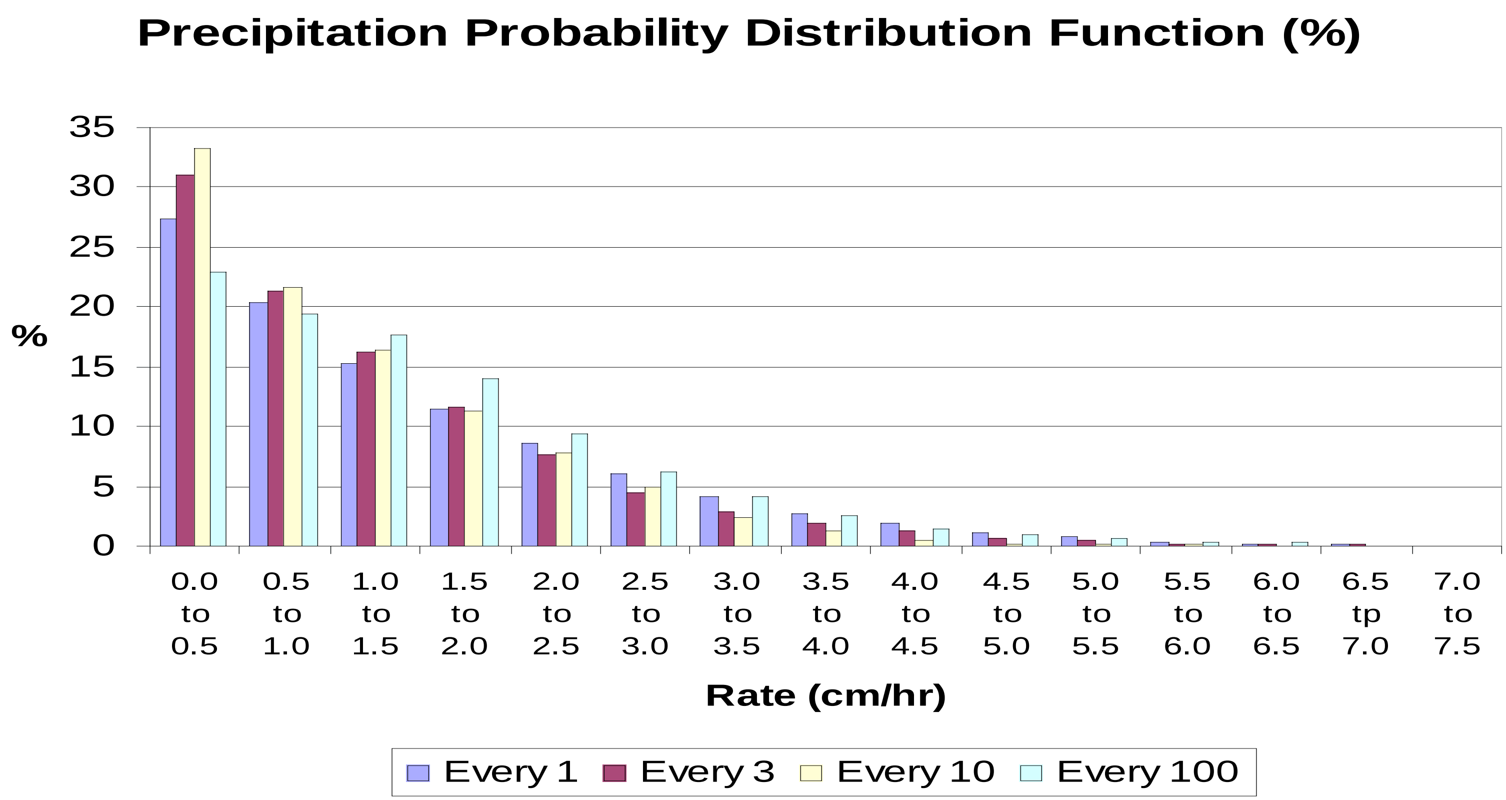
WRF-LIS Precipitation vs. Radiation Coupling Time Step

Eastman et al., GRL, 2006, submitted.



Total accumulated 24-hour precipitation (mm) for update frequencies at every (6 seconds), every 3 (18 seconds), every 10 (60 seconds), and every 100 (600 seconds) time steps.

Rain Rate PDF vs.Radiation Coupling Time Step



The WRF developers web site has now changed the users guide to suggest that a minimum of 10 timesteps be used for radiation updates

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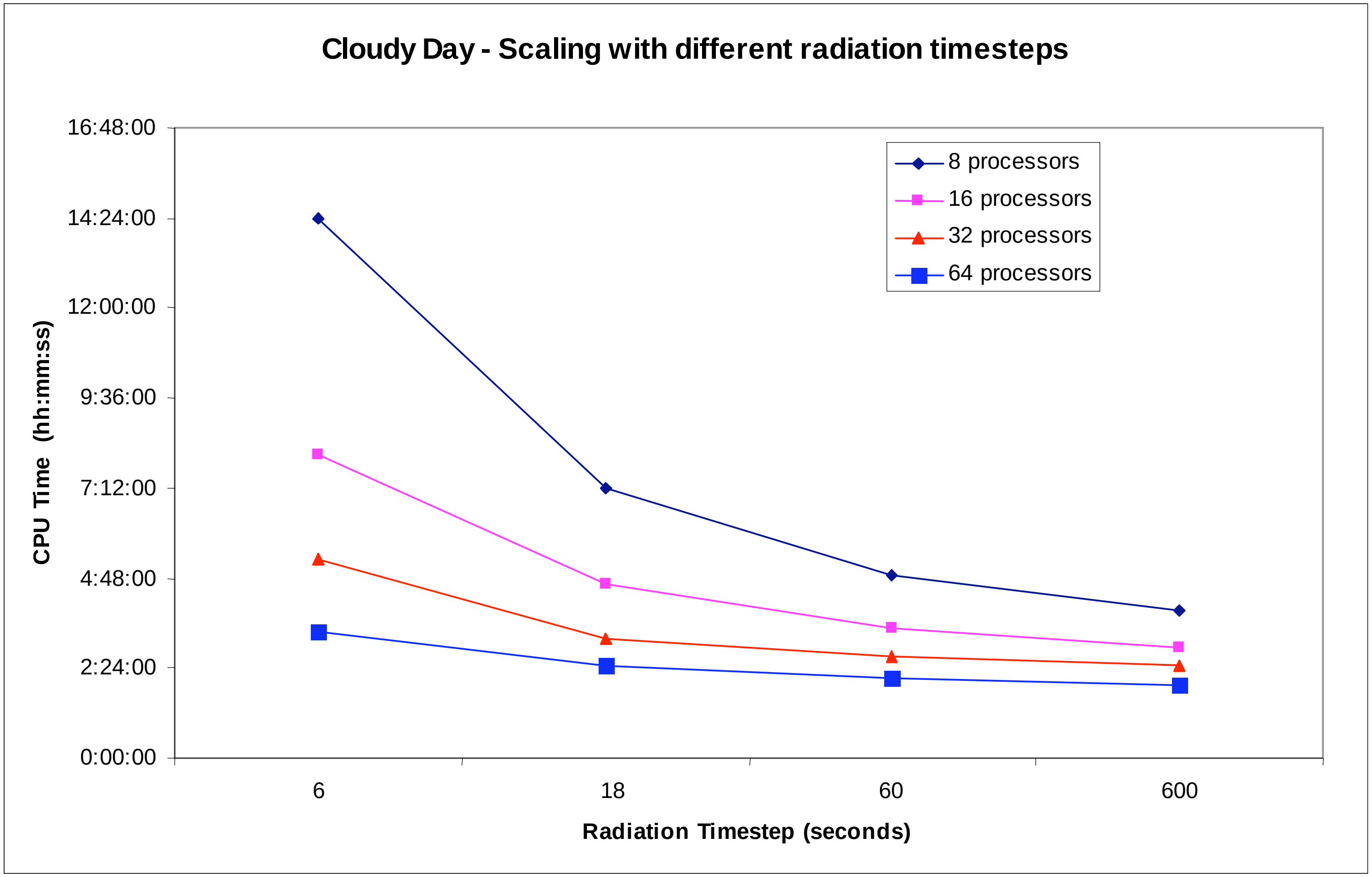
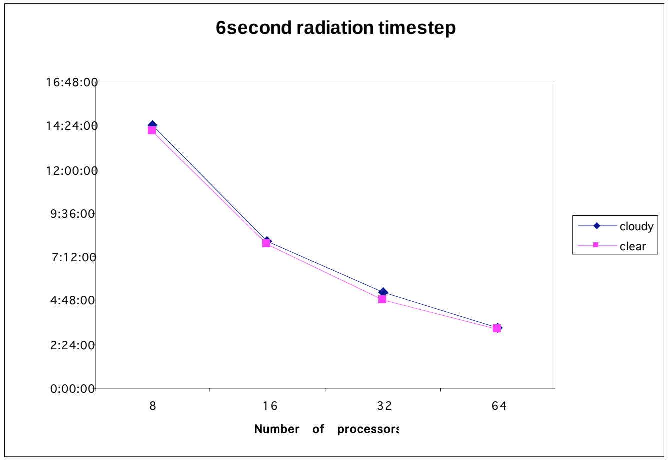
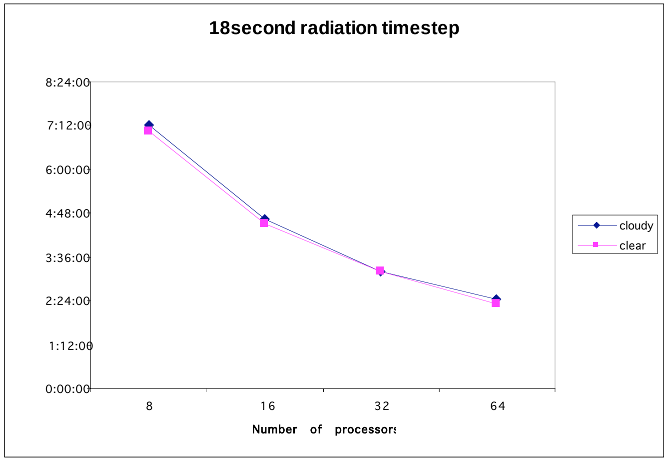
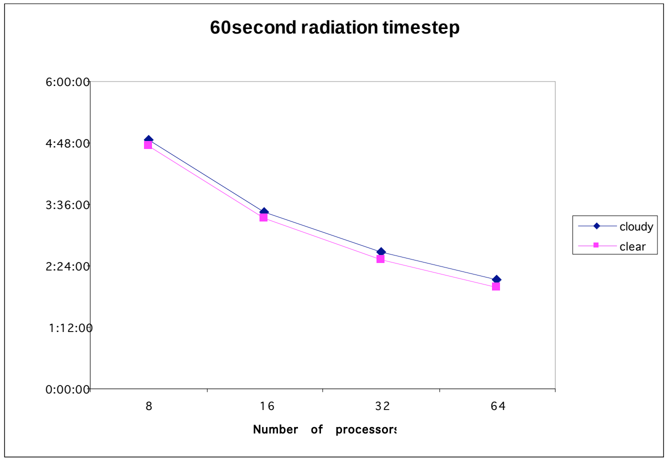
Computational Overhead of Increased Radiation Updates

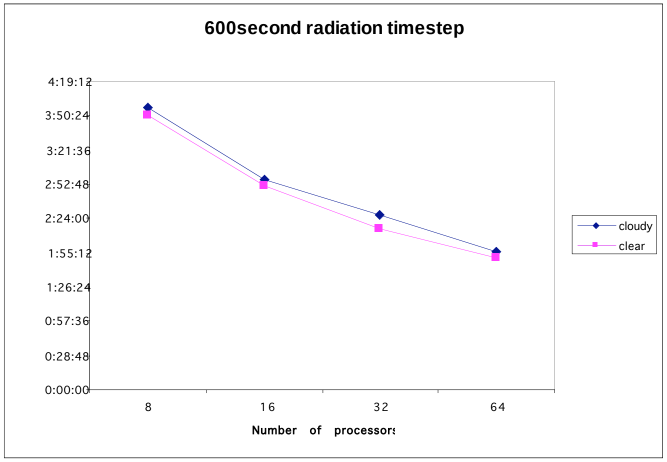


Performance Measures: Computational Overhead of Increased Radiation Updates









The slope of the clear/cloudy scaling curves is similar, indicating that the communication overhead is minimal, compared to the computational overhead. The computational overhead for cloudy days is higher compared to the clear days.

Project Highlights

TRL Advancement

- TRL3 technologies of LIS/WRF/GCE advanced to TRL5.

Recognition

- LIS won NASA 2005 Software of the Year Award.

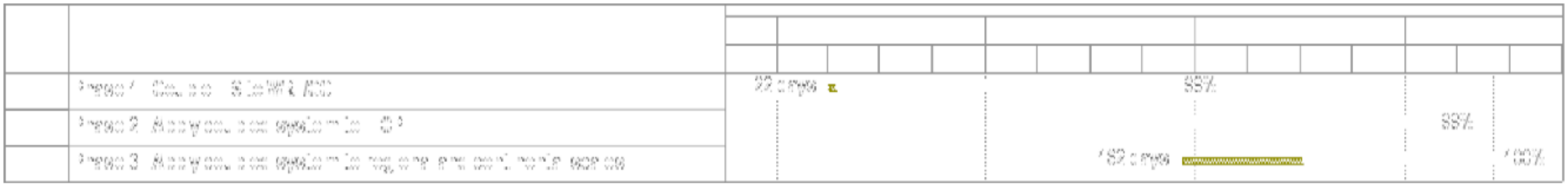
Technology Transfer to NOAA and DoD

- LIS is currently being benchmarked for potential operational use at NOAA's National Centers for Environmental Prediction, as well as the U.S. Air Force Weather Agency.

Benchmarking on Columbia

- The LIS-WRF-GCE code has been successfully ported to the Columbia supercomputer. Test cases were conducted to ensure consistent behavior.

Schedule Overview



Lessons Learned from Halem

- The CONUS-scale run requires approximately 50 GB of memory and runs in near-real time (requires approximately 22 hours for a day's simulation, using 128 processors). The near real-time is significant since the queues on halem have a maximum 12 hour limit. Since the simulations with 128 processors run in real time, we only need one restart, instead of 2 or more if a smaller number of processors are employed.

- The general_big queue that supports large processor runs were extremely helpful. However, the main bottleneck was the disk storage limitations.

- Using 30 minute output frequency, and 3 hour restart frequency, the CONUS LIS-WRF simulation requires (for a day of simulation): 68GB of WRF output + 27GB of LIS output + 37GB of WRF restart (at every 3 hours) + 3GB of LIS restart (at every 3 hours) ~ = 140 GB total (Assuming the old restart files are wiped out).

- The /scr space on halem, where the runs are typically conducted, has a quota limit of 145GB. So we can barely squeeze one run, with some monitoring and data cleanup.

- All the output is currently stored on the DMF on halem, but the data transfer back and forth requires approximately 10 hours. Hence a significant time is spent in data transfers. Similar latency was observed when the data was transferred to our local systems.

- Our group has a dedicated storage of 1.4TB on halem. Almost 80% of it is filled up with all the background high resolution data that LIS needs. This leaves us very little room to store any output, albeit temporarily.

Appendix
LIS Key Milestones

Complete

- *Aug. 2002: Install LIS Cluster at GSFC*
  - **200 nodes, 112 GB total memory, 22 TB total disk**
- *Mar. 2003: First code improvement (LIS2.0)*
  - **Implement global LIS at 5 km resolution**
- *May 2004: Second code improvement (LIS3.0)*
  - **Implement global LIS at 1 km resolution**
- *Jul. 2004: Interoperability demonstration (LIS3.1)*
  - **Implement LIS as a partially** ESMF-compliant land model component**
- *Dec. 2004: Customer delivery (LIS4.0)*
  - **Deliver LIS to customers at Goddard Modeling and Assimilation Office (GMAO), National Centers for Environmental Prediction (NCEP), Princeton, Center for Ocean-Land-Atmosphere Studies (COLA), Colorado State University (CSU), University of Arizona, etc.**

**July 2004 Milestone renegotiated due to delays in ESMF project

Project Publications

Publications

- Houser, Paul, Mike Bosilovich, Christa Peters-Lidard, and Wei-Kuo Tao, 2004: Ultra-High Resolution Observation-Driven Land Modeling Needed to Enable the Development of Global Cloud Resolving Earth System Models, 2004: GEWEX News, Vol. 14, No. 3, pp. 8-9.
- Kumar, S. V., C. D. Peters-Lidard, Y. Tian, J. Geiger, P. R. Houser, S. Olden, L. Lighty, J. L. Eastman, P. Dirmeyer, B. Doty, J. Adams, E. Wood, and J. Sheffield (2005), LIS - An Interoperable Framework for High Resolution Land Surface Modeling. Environmental Modeling and Software, in press and available online since October 2005.
- Eastman, J. L., C.Peters-Lidard, W-K Tao, S. Kumar, Y. Tian, S. E. Lang, and X. Zeng, 2006: A Meteorological Model's Dependence on Radiation Update Frequency, Geophys. Res. Lett., submitted.
- Zeng, X., W-K Tao, M. Zhang, C. Peters-Lidard, S. Lang, J. Simpson, S. Kumar, S. Xie, J. L. Eastman, C-L Shie, and J. V. Geiger, 2006: Evaluating Clouds in Long-Term Cloud-Resolving Model Simulations with Observational Data, Submitted to the Journal of the Atmospheric Sciences.
- Eastman, J. L., C. Peters-Lidard, W-K Tao, S. Kumar, Y. Tian, S. E. Lang, and X. Zeng, Sensitivity of Convective Modeling to High Resolution Land Surface Data Assimilation, Journal of the Atmospheric Sciences, In preparation.
- Kumar, S. V., C. D. Peters-Lidard, and J.L. Eastman, 2006: An Integrated High Resolution Hydrometeorological Modeling System using LIS and WRF. In preparation.
- Kumar, S. V. and C. D. Peters-Lidard, Evaluation of Multiple Radiation Products and an assessment of the sensitivity of the land surface states using Land Information System. In preparation.
- Peters-Lidard, C. D., P. R. Houser, Y. Tian, S. V. Kumar, J. Geiger, S. Olden, L. Lighty, B. Doty, P. Dirmeyer, J. Adams, K. Mitchell, E.F. Wood, J. Sheffield, 2006: High Performance